Understanding Clean energy and fuels from biomass

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Understanding

clean energy and fuels

from Biomass

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To

my grand children

Sunaina Raveesh and Nishanth Raveesh

for the affectionate persuasion to extend the stay

at Hereford, UK long enough to complete this book

सत्यमेव जयते
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Foreword

Biomass occupies an important energy source in rural India as well as in several developing countries of Africa and Asia. However, it is yet to find a place in the energy systems of the country. Its current deployment is inefficient and poor at emissions, thus contributing to undesirable in-door air quality. Combustion of biomass is widely thought to be smoky. What seems to be lacking is the proper application of science to understand the conversion processes and to provide satisfactory solutions that are affordable and accessible.

A serious debate on climate change is currently going on globally at several levels. Biomass can play a key role in stabilizing the environment particularly in developing countries since moving from inefficient to efficient use and discovering newer pathways of conversion by deploying modern tools of science and technology is likely to change the scenario significantly.

In the above scenario, an authentic book on biomass conversion is clearly meaningful and necessary. Professor H. S. Mukunda and his colleagues have been rigorously pursuing this subject for several decades ever since I was the Director of the Indian Institute of Science. I am delighted that Professor Mukunda has put together an excellent account of the foundations of biomass conversion to energy and fuels, drawing on the work done at the Institute along with the results from international efforts. I have no doubt that the book will not only be a textbook in academic institutions but also a reference book to all those interested in biomass, including policy makers and administrators.

I believe that students, teachers, consultants and practitioners will benefit a great deal from this study of a subject of great current interest. I do hope that it reaches the intended readership and helps to make progress in the energy and climate fronts.

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Preface

There are a number of books on biomass based energy in the literature. One of the excellent books is by Dr. Donald Klass entitled "Biomass for renewable energy - fuels and chemicals" generally addressing the interests of the USA. Perhaps, the interests of Europe and other developed countries are served by the technological approaches outlined in this book. There are also books on specific aspects discussed in this book. The book on gasification by Thomas B Reed provides the basic understanding on the subject in the eighties and that by Rezaiyan and Cheremisinoff on various technological features.

This book lays emphasis on relatively small size conversion systems of relevance to developing countries. Developing country problems are different from those of developed countries. In developing countries, land holdings are small because of large population and biomass fulfils the cooking energy demand significantly. Technologies in service of communities have to be at scales much smaller than those for developed nations. A MWe power station needs about 7000 tonnes of dry biomass annually. To obtain such biomass on a sustained basis is a task that needs to be addressed specially in a developing country, because there is competition for agro-residues for several requirements, some of which can come up due to sudden occurrence of draught. The scale of demand for biomass is much smaller in a developed nation and one can conceive of power stations that need biomass at ten to twenty times this value. Making available biomass for cooking is another issue of significant dimension. Cooking fuel use in India is about 300 mmt (million metric tonnes). While the possibilities of developing clean combustion solutions can bring down the use to about a third of this usage (100 mmt), these are not the subjects of primary exploration in research and development in advanced nations. Developing the alternatives and trying them out is essentially a developing country initiative. Biomass is used in cook stoves in most developing countries that include Africa, China and and most of Asia. In some countries charcoal is used at unsustainable levels with emissions much larger than wood stoves. There is a general lack of understanding the fundamental issues around this subject, for otherwise, the matters would not have remained as they are. While making progress on providing clean energy alternatives requires the synergy amongst many groups, they can take steps only when the fundamental scientific aspects are sound.

There are a large number of papers and documents on the broad subject of this book, but no book that the author is familiar with deals with the subject from a fundamental view point to enable understanding many issues that are important from the technology view point; for instance, many large power level technologies examined in the west are sought to be replicated in India with inadequate understanding of the scientific and technological issues with inevitable commercial ramifications. These can be avoided only with a proper understanding of the fundamental aspects.

The principal approach taken in this book is to describe and examine the processes involved in the conversion of biomass to energy or a more useful fuel (gas or liquid) from a suitable combination of laboratory study, a simple analysis, a computer simulation of the basic equations and field system performance. Such an approach can illuminate the subject enabling the reader to understand why some approaches succeed and others do not at the scale involved.

When biomass is conceived as a part of renewable energy source, it is thought of as one of four - "solar photovoltaic, wind, hydro and biomass, with biomass being the last item. It is little recognized that biomass is stored solar energy" through photosynthesis. Because it arises from a living process, its production does not stop at night or when there is no wind. Biomass is also responsible for five outputs - food, fiber, energy, liquid fuel and chemicals as against the other renewables that produce only one output - mechanical or electrical energy. The depreciated position on biomass is due to the general feeling that handling biomass is dirty and burning it produces smoke. This is where understanding of the processes of staged combustion with gasification and using modern technologies on optimal controlled air supply help in the design of processes for clean combustion of biomass by also reducing the impact of the variability in input properties - shape, size, moisture and ash content. The objective of this book is to provide an understanding of the fundamentals involved.

Chapter 1 introduces the role of biomass in the energy mix in India. The crucial point of the magnitude of biomass energy servicing the society is stressed.

Chapter 2 introduces the fundamental processes associated photosynthesis that is the basis of biomass production. An aspect of future science and technology development concerns ways of advancing the efficiency of photosynthesis. This chapter also brings out the amount of bioresidues available in India for energy purposes. Agricultural crops are grown with photosynthetic efficiency of 0.1 to 8 %. Sugarcane, potato and banana show high productivity. The maximum biomass produced is about 50 dry $t/ha/year$. Plantation wood production can reach about 25 dry $t/ha/year$. Efforts to grow bamboo at 50 dry $t/ha/year$ are being made. These make it possible to enhance the role of renewable energy in the energy mix of the country. The considerable culturable waste land in the country is suggested as being available for growing fuel crops instead of food crops without the fear of creating food vs fuel controversy in the country. This approach has the promise of replacing fossil fuel import by a significant amount.

Chapter 3 introduces the routes of conversion of biomass. It is recognized that wastes of biomass appear in a number of forms - those that have a large amount of water fraction in them and those that have relatively low moisture content. Those that have large moisture (active biomass content of 5 to 15 %) are better handled by low temperature processes mosty using microbial conversion routes. Those that have relatively small moisture (30 to 50 %) can be dried economically and converted to energy or fuels through a variety of thermochemical conversion routes. A large part of the biomass in the world is thermally converted to energy, fuels and chemicals.

Chapter 4 is concerned with a discussion of the chemical-thermodynamic basis of the conversion processes of biomass. Chemistry, stoichiometry of biomass with air and oxygen as the oxidizers are presented. Methods of calculating the adiabatic flame temperature and equilibrium composition are brought out. This knowledge is used to highlight the differences in the combustion behavior of biomass and fossil fuels in practical systems. The subject of large scale combustion systems aimed at obtaining high efficiency and reduced emissions is discussed. The issues of sodium and potassim in agricultural residues causing operational problems and ways of resolving them are discussed.

Chapter 5 is concerned with anaerobic treatment of domestic and industrial wastes. The discussion covers both these largely in liquid form - sewage and kitchen wastes from the domestic sector; solid wastes from kitchen and gardens and liquid industrial wastes from food processing units in a wide variety - alcohol, milk, fruit, starch and meat, as well as paper and pulp. Solid wastes also come from vegetable markets, poultry, urban dwellings and other industries. Anaerobic treatment is the only profit-centric alternative for primary treatment of liquid wastes. The case for treating waste streams with solids content better than 50 % and perhaps >30 % and rest water by anaerobic digestion is less clear. International effort has gone into building systems for these substrates as well. The performance is highly varying and coupling the waste treatment with disposal of final solids - the compost has led to problems of commercial operability of the plants particularly in India. The discussion includes a critical cattle manure based plants at domestic level as well as alternatives with other substrates like leafy biomass. An interesting new aspect discussed is a non-dimensional number defined by M = (OLR/COD) t_{res} or (VSL/VSC) t_{res} (OLR, VSL = Organic loading rate, Volatile solid loading, COD, VSC = chemical oxygen demand, volatile solid concentration) that reflects the operation of anaerobic digesters and the % COD removed or % converted will depend on M, the single parameter. This is being emphasized because literature is abound with the three parameters treated in an independent way.

Chapter 6 is concerned with discussing many aspects of gasification - principles, the results of experiments on gasifiers and the elements of technology that work, the emphasis being to connect the observations to the fundamental processes. In the study of the subject of gasification, it is brought out that the pathways of pyrolysis and chemical kinetics are stressed more than their true influence. That in reality a wide range of biomass with the same level of thermal content exhibit weak differences is traced to the aero-thermo-chemical nature of the process, Thus the role of pyrolysis becomes subdued; however, it may help identify the pathways leading to the chemicals in tars. Aspects of gasification including the different approaches and their characteristics are discussed. The unique approach of open-top staged air injection reactor design of Indian Institute of Science (IISc) is presented along with test results obtained in a joint campaign with Swiss scientists at IISc and in Switzerland. The inadequately appreciated role of moisture in biomass on the performace is strongly emphasized. The tar generation in reactors as a function of size of the biomass that afflicts the operation of gasification systems is explained in terms of a non-dimensional number that is the ratio of the mean value of minimum thickness to the residual char. The presence of ash with potassium and sodium is also serious for smooth and steady functioning of the reactor and ways of dealing with this problem through suitable aero-thermo-chemical design are brought out. The issues of cooling waste water treatment is also discussed.

Chapter 7 is concerned with high grade heat or electric power from producer gas. Several routes for energy have been discussed. High grade heat from piped gas into a specific location in an industry is a direct possibility most usually in a dual-fuel mode with either mode being used without having to mix them allows the user to combine economic operation with availability. When it concerns electricity generation, the use of diesel engines needs a limited diesel injection for ignition in dual-fuel mode. Gas alone mode using spark ignition engines allows for high gas-to-electricity efficiency of 37% with large engines and of 30% with small engines. Issues of emissions from engines and ways of reducing them are discussed as well. The strengths of reciprocating engines vis-a-vis gas turbine engines are discussed bringing issues normally lost sight of in the first instance. Fuel cells have been emphasized for the possibility of enhanced efficiencies and it is suggested that economics related to first cost is the only impediment. Its support in advanced countries for stationary power generation will take time to create commercial availability except in niche applications.

Chapter 8 is concerned with a discussion of stove designs that are based on “gasifier” ideas, the theme of chapter 6. A gasifier stove is evolved by inverting a downdraft gasifier, Optimizing the efficiency and emissions to meet a cooking cycle needs an engineered “solid fuel” of high density best based on agricultural residues. A near-constant throughput of gaseous fuel due to gasification and a correct air-to-fuel ratio used for combustion of the gases are shown to be the basis of the good performance. Another design with horizontal gasifier is shown to meet the objectives of a continuous stove whose efficiency and emission performance with any dry fuel will be comparable to the reverse downdraft design.

Chapter 9 is devoted to describing two pyrolytic processes – slow and fast. While slow pyrolysis is the basis of gasification a subject addressed already in the earlier chapters, what is addressed here is a special fuel called torrefied biomass with higher energy density with hydrophobic quality and lends itself to pulverization that is less energy intensive. It can be pelleted or briquetted to help economy in transportation. Pyrolytic oil is a result of fast pyrolysis. Pulverizing dried bio-residue to sizes less than a mm and heating the material at a thousand K/s or better to temperatures around 500°C will generate about 65% of the dry biomass as pyrolytic oil. This oil has a LCV of 17 to 19 MJ/kg and has about 15% water in an azeotropic mix with oil. It has fine carbon in it that must be filtered out. Its current use as a food flavoring agent appears more commercially attractive than for energy applications. Both these have yet to find a commercially relevant space in the energy market.

Chapter 10 deals with liquid biofuels - ethanol and biodiesel. It is titled biorefinery because any large scale implementation that will influence the economy and preserve the environment calls for an integrated approach in which the variability of the feed stock and the needed output need to be matched considering the seasonal availability of many of the feedstocks considered. Of course, independent operations are entirely possible. The first generation fuel technologies – ethanol from sugars and starch and biodiesel from plant oils are ready for scaling up to levels that can make a difference to the economy of countries like India. Cellulosic ethanol technology has elements like preprocessing strategies as well as appropriate enzymes that need to be researched. These are described in some detail to provide insight to an initiate to the field of energy. Gasification route has several pathways. The most appropriate strategy for countries like India would need to be sized at capacities lower compared to those conceived in Europe and the USA. This suggests the choice of a fixed bed system for handling the solid fuels that needs further research. Fischer-Tropsch process has always remained elusive for realization due to the economy of scale but must be combined with gasification process for making the technology relevant to developing nations. It is suggested that growing algae for both lipids (first generation diesel) as well as a source of biomass should also be kept in mind in dealing with sustainability of the supply of feedstock.

Chapter 11 is concerned with urban solid waste, USW (or municipal solid waste, MSW) conversion technologies. The novel thermal processes are described here. Pyrolysis, gasification and combustion technologies (discussed elaborately in earlier chapters) with overlapping ideas have been used to develop the technologies. The crucial elements of most technologies would be to separate the recyclables and transfer the organics for waste treatment. Two broad approaches here are: those that introduce oxygen or highly enriched air to melt the remaining inorganic material consisting of sand, grit and glass and metals that escaped the separation process and those that tolerate it in the conversion process and dispose off the ash into landfill. Other relevant aspects for strategies for developing countries are brought out.

Chapter 12 is concerned with several technologies that have been in existence for a long time and yet have not found their place in the commercial energy scenario. Stirling engine, thermoelectric device, direct carbon fuel cell, algae are discussed bringing out the crucial current appreciation of the basic aspects.

This book includes in several chapters the understanding derived from the work over the last thirty years at IISc in the area of thermochemical conversion for domestic and industrial heat as well as electricity. Several colleagues - Prof. P. J. Paul, Dr. S. Dasappa, Dr. N. K. S. Rajan have been the partners in the scientific and technical voyage all the time. Drs. G Sridhar and H. V. Sridhar made substantial contributions to the gasification technology before moving on to take other responsibilities. Mr. Subbukrishna has made important contributions to hydrogen sulfide scrubber technology and later to gasification technology, more particularly with respect to charcoal generating gasifiers and waste water clean up systems. Many technicians have taken care to operate the gasification and other systems to inspire confidence in administrators, investors, prospective collaborators and users as well as curious visitors. They have created a foundation what impressive power point presentations alone cannot do.

Acknowledgements

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Prof. Bhaskar Dixit, my former student provided a useful review of the initial drafts of the book. Dr. P. R. Nagasrinivasa, my classmate from undergraduate studies in engineering reviewed the draft and provided valuable inputs on the general readability of the text and many errors have been corrected due to his inputs. Dr. G Sridhar, my former student and currently in Siemens, India has provided useful inputs on chapters concerning thermochemical conversion. Sri. Anil K Dhussa of MNRE has provided critical and valuable ideas apart from system specific information on the chapter on biomethanation. Dr. Hoysala Chanakya, my former colleague has provided insightful inputs on the chapter on biomethanation and several other useful observations. It is a pleasure to record my grateful thanks to all these friends.

H. S. Mukunda

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Contents

List of Figures

List of Tables

1 Introduction

1.1 The energy mix in India

It is important to know how the energy needs of the communities in India is being met with - from what sources and how much. Table 1 shows the usage pattern in million metric tonnes (mmt) on an annual basis from the sources in current use (IEA, 2007; IEA, 2006; MPN, 2010; MOP, 2010; MNRE, 2010, Pandey, 2002; Ravindranath and Hall, 1995). Table 1.1 is very instructive. Grid linked power stations with a total capacity of 75000 MWe depend on coal. Natural gas is also a source of electricity generation where it is available, though its more important role can be as a chemical feed stock. It is used to a very limited extent as a cooking fuel in some major cities where piped distribution of the gas is arranged. High speed diesel is a heavy vehicle transport fuel on much economic transportation is dependent. Naphtha and light diesel oil are typical fuels in stationary gas turbine engines and reciprocating engines for electricity production. Fuel oil, otherwise termed as furnace oil is used for heat at high temperature in chemical industries, steam raising in other industries and as a fuel in large reciprocating engines (typically of 2 to 5 MWe class). The low sulphur heavy stock is typically meant for reciprocating engines for electricity production. The fuels - HSD, LDO, LSHS, FO can be used in reciprocating engines with compression ignition. The fuels ignite in an atmosphere

Table 1.1: Fuels, Lower calorific value (LCV), usage and purpose (for India for 2007-2008)

Fuel	LCV MJ/kg	Usage $mmt/year$	Purpose
Coal	20	400	Electricity
		20	Steam raising/heat
Natural gas	50	12	Electricity, transport, cooking
HSD	42	40	Heavy vehicle transport
Naphtha	42	12	Stationary power generation
LDO		2	
FO/LSHS	40	14	Electricity via diesel engine
Gasoline	42	9	Vehicle transport
Kerosene	42	12	Cooking/transport
LPG	45	10	Cooking, urban transport
Firewood	16	250	Cooking, electricity, industry and rituals
Agro-residues	14	120	
Cowdung	13	40	

HSD: high Speed Diesel, LDO =Light Diesel Oil; FO = Fuel Oil (or Furnace Oil)
LSHS = Low Sulphur Heavy Stock, LPG = Liquified Petroleum Gas

of high pressure hot air close to the end of compression, a little earlier to reaching the top, the TDC (Top Dead Center), as it is termed.

Gasoline is a fuel used in spark ignition reciprocating engines used on light motor vehicles - cars and very low capacity power generating sets. Kerosene can also be used similarly, but using it directly in the place of gasoline is not the appropriate thing to do. This is because gasoline vaporizes and passes into the combustion chamber as a mixture of air and fuel vapor. Kerosene does not vaporize well and hence has to be introduced in the form of fine droplets into the combustion chamber. This does not produce the best of the combustion inside the engine designed to run on gasoline. Liquified petroleum gas is a mixture of butane, propane and methane to a small degree. The properties are governed largely by butane that constitutes about 75 to 85 % of the mixture. Under a self generated pressure of a few atmospheres (typically 3 to 7 atms. - 3 to 7 times the atmospheric pressure of 101.35 kPa, kiloPascals) depending on the temperature at which the mixture is maintained (typically, 25 to 30°C), the mixture turns into a liquid. It is treasured as a cooking fuel because of the convenience of instant start and stop, variable power and clean combustion. Cooking devices - stoves also allow for high efficiency of utilization. It is also used as a motor fuel, particularly for three-wheelers and small cars in urban transportation.

Solid bio-fuels like firewood, agro-residues and cow-dung constitute the primary cooking fuel of large rural population in developing countries. In India, 700 million people constituting 70 % of the population living in about 140 million house-holds depend on these fuels for daily cooking. LPG has reached a very small fraction of the rural population. Even in these cases, solid bio-fuels are used for major cooking allowing LPG to be used sparingly and for use under demanding circumstances. The solid bio-fuels are used in such devices that are energy inefficient and very polluting. It is almost a maxim that when people are told of cooking on firewood or agro-residues, smoke and tears come to their mind. Energy-wise, the solid bio-fuels constitute nearly 100 *mmt* of oil. However, allowing for the best possible efficiencies of utilization, the energy equivalent is about 75 *mmt* of oil equivalent. This is indeed a staggering number and there is little public realization of this magnitude. Hence, there is much to be gained economically and environmentally by improving the utilization efficiency and reducing the emissions. This can only be accomplished by a better understanding of the processes of conversion. This understanding coupled with the realization of practical devices has occurred only in the last decade.

There are important differences in the energy conversion processes of fossil fuels like LPG, diesel, gasoline and kerosene as well as solid fuels like coal and biomass. In the case of LPG, the conversion process is in a single phase, namely gaseous. In the case of diesel and other liquid fuels, conversion process involves vaporization and there is no residue. In the case of solid fuels, the conversion process occurs in two stages. In the first stage, volatiles get released from the condensed phase and these volatiles burn up with the oxidant - oxygen in a mixture of oxygen and nitrogen (air is one standard case with 21 % volume of oxygen and the rest largely nitrogen), At the end of this process, char is the active solid residue that burns by a surface reaction with oxygen diffusing from the gaseous phase. The first phase is usually termed as flaming combustion and the second, glowing combustion. Most natural solid fuels have some inorganic components that would have gotten into the material because of the growth process. The magnitude of this varies from about 0.5 % in some woods to as high as 20 % in rice husk and straw. This will inevitably be left behind as ash. Char conversion with 0.5 % ash level in the biomass is vastly different from that with 20 % ash level since at this large ash level, the active carbon is only 50 % of the total material.

One can burn (or combust) the biomass directly with appropriate amount of air or convert the solid fuel into a gaseous fuel (called producer gas) through a high temperature process with air at less than the amount (at 30 %, typically) required for complete combustion. One can replace the air by oxygen or/and steam to generate combustible gases called synthesis gas rich in hydrogen. These gases can be subject to treatment to separate hydrogen. Alternately, the gases can be subject to high temperature-high pressure catalytic process termed Fischer-Tropsch process to get liquid hydrocarbons. Usually, one gets a mix of hydrocarbons and they need to be separated to get desired fractions - diesel, gasoline, etc.

Biomass composition on a structural basis (as different from ultimate and proximate analysis relevant to the discussion above) is relevant to bacterial conversion processes. Biomass is composed of cellulose (whose fibrous structure provides strength), hemi-cellulose (that is similar to cellulose) and lignin that provides the binding. It turns out that bacteria can deal with cellulose (and with much greater ease, sugars and starch) but not lignin. Lignin needs fungus for the conversion process. Bacterial conversion processes can be aerobic or anaerobic. Anaerobic conversion processes allow for the production of gases rich in methane (called biogas). These gases after suitable pre-treatment can be used for enriching the gas to methane or for power generation by use in spark ignition engines.

1.2 The role of biomass in the energy mix

What is particularly striking is that the magnitude of biomass currently used is large and comparable to mainstream fuels, even if it is inefficient and polluting. Coal, the principal fuel on which large power generation depends is largely produced in the north eastern belt of India. Figure 1.1 shows the distribution of coal in India. Notice that it is distributed unevenly and most of the coal mining is restricted to the north-east of the country. Also, Indian coal that is used for power generation purposes has ash content up to 45 %. Special washing procedures are used to bring down the ash content to about 25 % to ensure economy of long distance transportation to power stations distributed all over the country.

The advantage of biomass against coal is its availability all over the country even though it is seasonal. The total agricultural residues annually amount to more than 500 mmt, 75 to 80 % of which gets used as fodder for livestock and other societal needs. It is estimated from rigorous studies that about 100 to 120 mmt is available for energy purposes. One stated disadvantage of biomass is its low density - 200 to 500 kg/m^3, about 20 to 50 % of the density of water, making transportation costs an important factor in the design of energy generation system. This stated disadvantage can be taken advantage of by designing distributed generation and utilization schemes. If, for instance, one needs prepared cooking fuel of high density, one can process the agricultural residues into pellets of high density locally to help reduce long distance transportation costs.

1.3 Biomass and Environment

Biomass was and continues to be the backbone of energy for cooking for over 500 million households, mostly in the developing and emerging part of the world that includes most of Africa, significant parts of India, China and other countries in south-east Asia. Two aspects that have been known for a long time are that (a) improved efficiency in cooking is a desirable feature and (b) reduced emissions of CO and particulates are important for improving the indoor air quality in the kitchen and thus contribute to improved health [IEA, 2006, Mukunda et al, 2010].

Figure 1.1: The distribution of coal over India

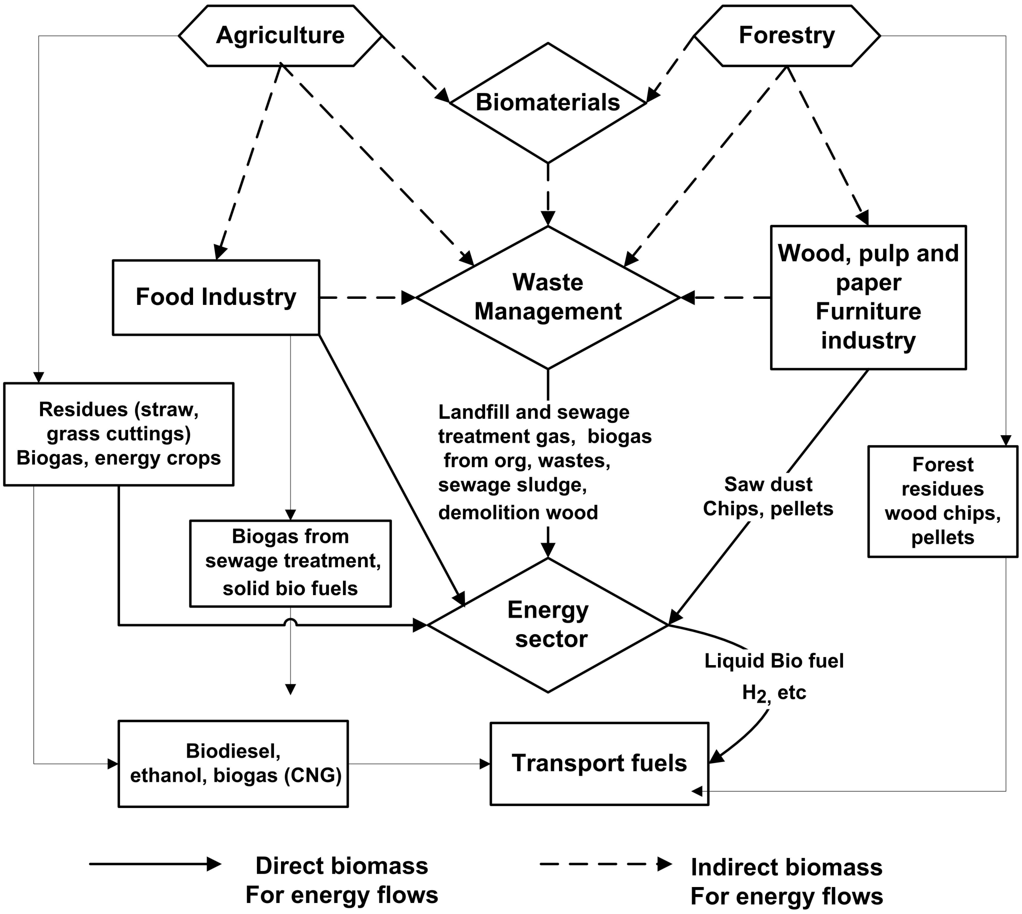

Figure 1.2: The biomass flows, direct and indirect with inevitable wastes that can be used for the generation of energy – electricity, fuels for transport and heat; CNG = Compressed natural gas, adapted from GEF (2006)

There are a large number of stoves that use chimney to take away most of the emissions out of the kitchen. This encourages most often laxity in the operation of the stove and the result is that significantly larger undesirable emissions get into the atmosphere. Across the World, the amount of biomass used exceeds 800 mmt most of it at efficiencies of 15 ± 5 %; the emissions constitute CO, particulate matter (PM) and other poly aromatic hydrocarbons due to incomplete combustion. Typically the emissions are about 30 - 40 g CO/kg biomass and 0.2 - 0.5 g PM/kg biomass (the particulate matter is identified as PM10 and PM2.5 referring to particle sizes of 10 and 2.5 microns respectively). Opportunity exists to raise the utilization efficiency to around 50 ± 5 % (implying conservation of 600 mmt of fuel and limiting the CO emissions <10 g CO/kg biomass and particulate matter to <0.1 g/kg biomass. The implications of such developments to improving the indoor and outdoor air quality are very significant.

Much of this was considered desirable till a time when climate change issues were not dominant. Now, that the climate change issues have been considered as serious internationally, it appears far more compelling for all concerned to act for the benefit of all including the environment along the lines described above.

The movement on greening the environment gains from the need to sequester the carbon from the atmosphere. A very important finding of recent times is that converting biomass to bio-carbon (biochar) in addition to energy and ensuring that the bio-carbon goes into the soil may have very significant positive environmental impact [Lehmann, 2009, Whitman and Lehmann, 2009]. Specifically, it has been found that the life of such biocarbons within the soil is long - more than several hundred years. This goes beyond the life of carbon dioxide in the atmosphere. The argument is therefore, that such an approach offers carbon negative environment and energy strategy.

Thus, (a) growing biomass by using the science of photosynthesis as well as is possible, (b) using the biomass more efficiently for energy purposes and (c) depositing the fine residual carbon into the soil will create a win-win-win situation for energy support for the society. In addition, it will also help preserving the environment by sequestering the carbon and the creating a society less dependent on fossil fuels for living.

The overall approach to the use of biomass for energy is best summarized in a document of GEF-STAP (Global Environmental Facility - Scientific and Technical Advisory Panel), GEF (2006). Figure 1.2 shows the various sources of wastes and ways of producing energy - electricity, transport fuels and chemicals. To this list must be added solid fuels for cooking using modern technologies. The clear point that comes through is that the utilization chain is based on wastes and any competition between these uses and other uses (like for food) should be avoided as much as possible.

1.4 Summary

In this chapter, the total energy profile of India is introduced to establish the role of renewable fuels like biomass in the energy mix. We recognize that the amount of coal used is only slightly larger than biomass. Coal is used in power plants at end use efficiencies between 30 and 35 % for electricity generation and biomass is used largely as domestic fuel in a distributed manner at end use efficiencies of 10 to 20 %. Thus there is much opportunity to improve the end use efficiencies and reduce the magnitude of the use of biomass or alternately, the biomass can be used to generate far more useful energy than is done presently. These can be done provided there is understanding of the processes involved and devices of high efficiency use can be designed and deployed.

Changing the paradigm of living from fossil based approach to renewable energy based approach has a friend in the climate change issue that has been largely due to fast use of fossil fuels in this century. For actions related to these to make a contribution, understanding of the science of clean energy from biomass is essential. This is the subject matter for the chapters to follow.

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2 What biomass? production, magnitude and location

2.1 What biomass?

Biomass that is used for energetic purposes is classified in terms of (a) agricultural residues, (b) plantation residues and (c) urban solid waste. Agricultural residues are produced with a cycle time of a few months or up to a half-year. In fact, some of the agricultural output is obtained twice or three times an year by growing same or different crops on the same land. Plantation residues arise from plantations that grow trees for several purposes - woody trees for paper industry, rubber trees for rubber, coconut trees for coconut or any other tree plantation that requires minimal input and attention, but generates output after several years at which time the entire plantation is harvested. Urban solid waste is the waste of large communities in cities with inadequate local eco-friendly disposal techniques. Both liquid and solid wastes are generated. Liquid wastes include sewage, kitchen and food wastes that have a solid content of a few percent, certainly less than 10 % or so. Solid wastes consist of garden wastes, vegetable prunings, house hold goods - broken furniture, clothing paper, packings along with plastic wastes including packings, carry-on bags, foot wear and so on. The per-capita magnitude and composition of the waste depends on whether it arises from a metro or a middle sized town since cultural practices differ significantly. Many a time, this waste is mixed with glassware, metallic materials, and building demolition wastes that involve cement, mortar, bricks and the like. For the purposes of energy, other wastes have to be separated and the, biomass will be the largest fraction with moisture content varying from 30 to 70 % depending on the season including festivities.

We can now examine what biomass is.

2.2 What is biomass? How is it produced?

Biomass is biological material derived from living, or recently living organisms. In the context of biomass for energy, biomass is often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material [Internet-1, 2010]. The reference to “recently” living organisms is brought out to exclude fossil derived material (like coal).

Unlike animals, plants manufacture their own food called “biomass” by the process of photosynthesis. And photosynthesis is the process where the green pigment in the plant’s leaf (called chlorophyll) absorbs energy from sunlight and reaction pathways are created between water from the soil, and carbon dioxide from the atmosphere to produce oxygen and simple sugars, like glucose and sucrose. The plant then uses these sugars to make more complex sugars and starches for storage as energy reservoirs and to produce cellulose and hemicellulose for cell walls or with nitrogen, to make proteins.

The emphasis on water from the soil and carbon dioxide from air may seem exaggerated. However, it took about *two hundred years* before the essentials as we know today were uncovered and it is a fascinating history [Xiong, 2000] - several stages to understanding through simple experiments, many of which can be repeated even today in school laboratories.

Aristotle (384 to 322 BC) had presented a view that the earth is like the stomach of plants as they gain their nutrients directly from earth and water without having a “proper” digestive system.

In 1648, Jan Baptista van Helmont, a Flemish scientist, carried out a famous experiment by growing a willow tree in a pot for five years. At the end of this period, the tree had increased in mass by 74 kg but the mass of the soil had changed little. He believed that water was the source of the extra mass and the plant’s source of life and not the soil.

In the late sixteen hundred, John Woodward tried to design an experiment to test Van Helmont hypothesis that water was the source of the extra mass. In a series of experiments over as many as 77 days, Woodward measured the water consumed by plants. For example, one plant showed a mass gain of about 1 g, while Woodward had added a total of almost 76 kg of water during the 77 days of plant growth - this was a typical result. Woodward correctly suggested that most of this water was drawn off and conveyed through the pores of the leaves and exhaled into the atmosphere. Thus the hypothesis that water is the nutrient used by plants was rejected. He also demonstrated that spearmint grew better in water containing soil than in rainwater alone.

In 1771, Joseph Priestley, put a bunch of mint into a transparent closed space with a candle that burned out the air (oxygen was not discovered yet) until it went out. After 27 days, he relit the extinguished candle again by focusing sun light beams with a mirror on to the candle wick as an ignition source and the candle burned normally in the atmosphere that did not support the combustion earlier. This proved that plants somehow change the composition of the atmosphere. We now know that carbon dioxide that was produced during combustion in the initial stage was used by the plant for its growth and in this process, oxygen got released. In another celebrated experiment, in 1772, Priestley kept a mouse in a jar of air until it collapsed. He found that a mouse kept with a plant would survive, again, establishing a fact that is considered well known today: plants breathe-in carbon dioxide and breathe-out oxygen. Jan Ingenhousz took Priestley’s work further and demonstrated that it was light that plants needed to make oxygen (oxygen was discovered a few years earlier, in 1772 by Carl Wilhelm Scheele). Ingenhousz was mistaken in believing that the oxygen made by plants came from carbon dioxide. However, he became the first person to show that light is essential to the plant process that somehow purifies air fouled by candles or animals. Later, in 1779, he put a plant and a candle into a transparent closed space. He allowed the system to stand in sunlight for two or three days. This assured that the air inside was pure enough to support a candle flame. But he did not light the candle. Then, he covered the closed space with a black cloth and let it remain covered for several days. When he tried to light the candle it would not light. He concluded that somehow the plant must have acted in darkness like an animal. It must have breathed, fouling the air and plants need light to purify the air. This confirmed the results of Joseph Priestley.

One of the important questions in that period was on the origin of ash left behind when dry plant burns. It was explicitly shown that the origin of the plant ash was soil based on experiments on synthetic soil vs. sand alone.

In the year 1817, Pelletier and Caventou isolated the green substance in leaves and named it chlorophyll.

In 1864, the first accurate measurements of the gas exchange were made and it was found that the volume of O_2 evolved is about the same as the CO_2 used up. Investigations in 1862-64 revealed the synthesis of starch under the influence of light and in relation to chlorophyll.

2.3 Plant, its features and growth process

The principal elements of the plant growth are: (a) photosynthesis (b) respiration, (c) transpiration and (d) photorespiration. An additional aspect concerns photo-respiration. These are described below.

a Photosynthesis is the bonding together of CO_2 with H_2O to produce a carbohydrate, CH_2O and O_2, using the sun's energy. The sugar contains the stored energy and serves as the raw material from which other compounds are made.

b Respiration is the opposite of photosynthesis – the stored energy in the sugar is released in the presence of oxygen, and this reaction releases the CO_2 and H_2O originally brought together by the sun's energy.

c Transpiration is a process of water evaporation out of stomata when they are open. This draws water and nutrients up to the top of the plant, but causes the plant to lose water and potentially dehydrate.

d Photo-respiration is a process that occurs under high light and heat; an enzyme called RUBISCO (see later for further discussion) that draws carbon dioxide for photosynthesis may draw oxygen instead, causing respiration to occur instead of photosynthesis, thus causing a slowing of the production of sugars from photosynthesis.

2.3.1 Photosynthesis

The subject of photosynthesis is extensively discussed subject on the internet. There are many presentations from various perspectives (see Vim Vermaas, 1998 and video in ref. internet-4) The principal features of a leaf (of a plant) responsible for the photosynthesis are shown in Figure 2.1. The components are many with widely different and complex biochemical functions. Evolutionary process has embedded into it a variety of capabilities to combat changes in surroundings and weather. The chloroplast is bounded by a double membrane: the outer membrane contains proteins that render it permeable to small molecules (Molecular Weight < 6000); the inner membrane forms the permeability barrier of the organelle. Photosynthesis occurs on the thylakoid membrane, which forms a series of flattened vesicles (thylakoids) enclosing a single interconnected luminal space. The green color of plants is due to the green color of chlorophyll, all of which is localized to the thylakoid membrane. A granum is a stack of adjacent thylakoids. The stroma is the space within the inner membrane surrounding the thylakoids. Stomata are the pores in leaves (and stems) through which CO_2 is taken in and O_2 is released during photosynthesis. The extent of their opening depends on the environment.

In the plant leaf shown in Figure 2.1, photosynthesis occurs only in the mesophyll layers that occupy the bulk of the leaf. and, mesophyll cells are sandwiched between the leaf's upper and lower epidermis and contain numerous chloroplasts. These chloroplasts contain several pigments, namely, chlorophyll (varieties, a, b, c1, c2, d), carotenoids (carotene, lycopene and

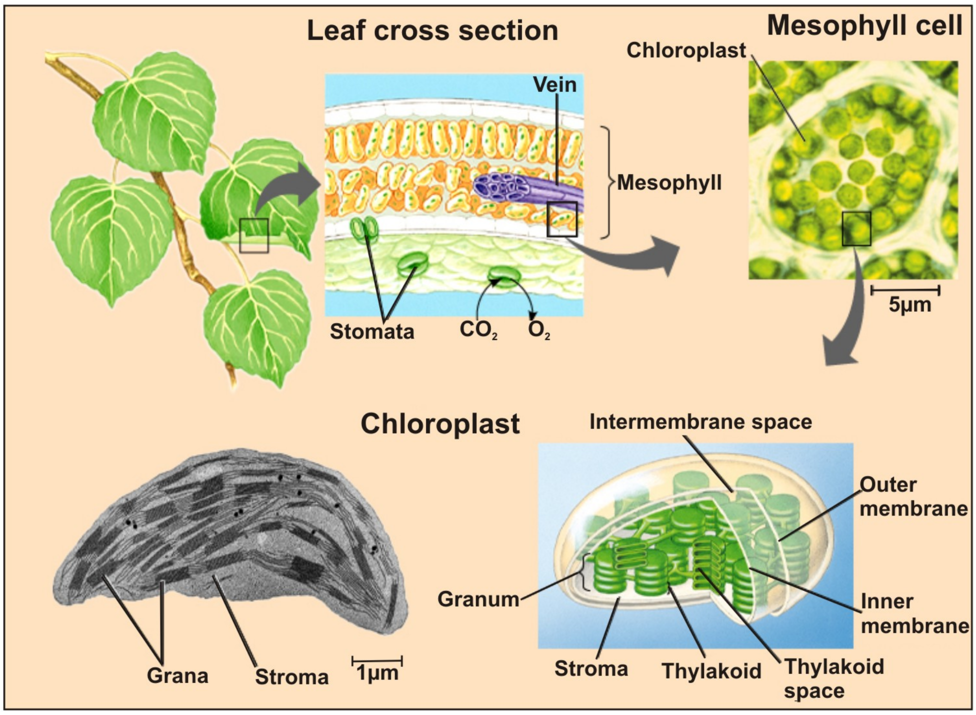

Figure 2.1: The structure of a leaf and chloroplast

Table 2.1: Pigments. chemical structure and colours

Type	Molecular formula	Occurrence and colour
Chlorophyll-a	$C_{55}H_{72}O_5N_4Mg$	Universal, bright green
Chlorophyll-b	$C_{55}H_{70}O_6N_4Mg$	Mostly plants, dull or olive green
Chlorophyll-c1	$C_{35}H_{30}O_5N_4Mg$	Various algae, green
Chlorophyll-c2	$C_{35}H_{28}O_5N_4Mg$	Various algae, green
Chlorophyll-d	$C_{54}H_{70}O_6N_4Mg$	Cyanobacteria, green
Caretene	$C_{40}H_{58}$	Leaves, vegetables, fruits, yellow
Flavone	$C_{16}H_{14}O_2$	Vegetables, fruits, Yellow
Flavanol	$C_{16}H_{14}O_3$	Vegetables, fruits, Yellow
Anthonycin	$C_8H_7N_3O_5$	Red, blue, purple and magenta

xanthophylls) and flavenoids (flavones, flavonol and anthocyanin). Chlorophyll-a is directly involved in the light reactions of photosynthesis. Chlorophyll-b assists chlorophyll-a in capturing light energy, and therefore it is called an accessory pigment. Other compounds found in the thylakoid membrane are carotenoids (carotenes). By absorbing colors that chlorophyll a cannot absorb, the accessory pigments enable plants to capture more of the energy in light. These pigments all absorb different colors of sunlight as shown in Table 2.1. As can be noticed from this table, all the chlorophyll compounds have Magnesium. Figure 2.2 shows the structure of chlorophyll-a. The most interesting part is the nature's choice of Mg element in the structure of chlorophyll. The variants of chlorophylls have structures with small variations over what is presented above. Other pigments also have complex structures. The absorption spectra of some of these ingredients are shown in Figure 2.3. Photosynthesis occurs due to these pigments. Chloroplasts are very tiny and their population density high – $0.4million/mm^2$. Parts of the mesophyll along with the inter-cellular air spaces allow for the interchange of gases. If one

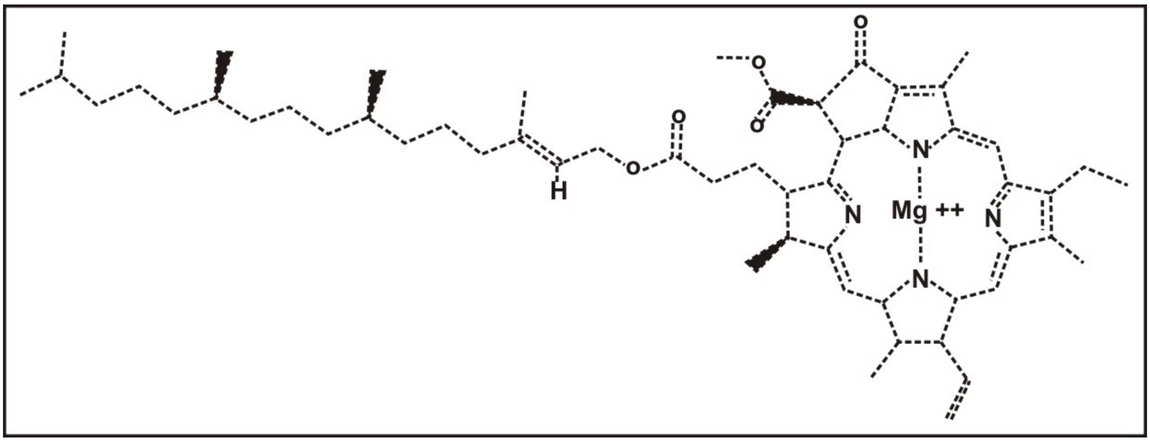

Figure 2.2: Structure of chlorophyll-a. Notice the Magnesium ions (Mg^{++}) centred complex pentagonal ring structure

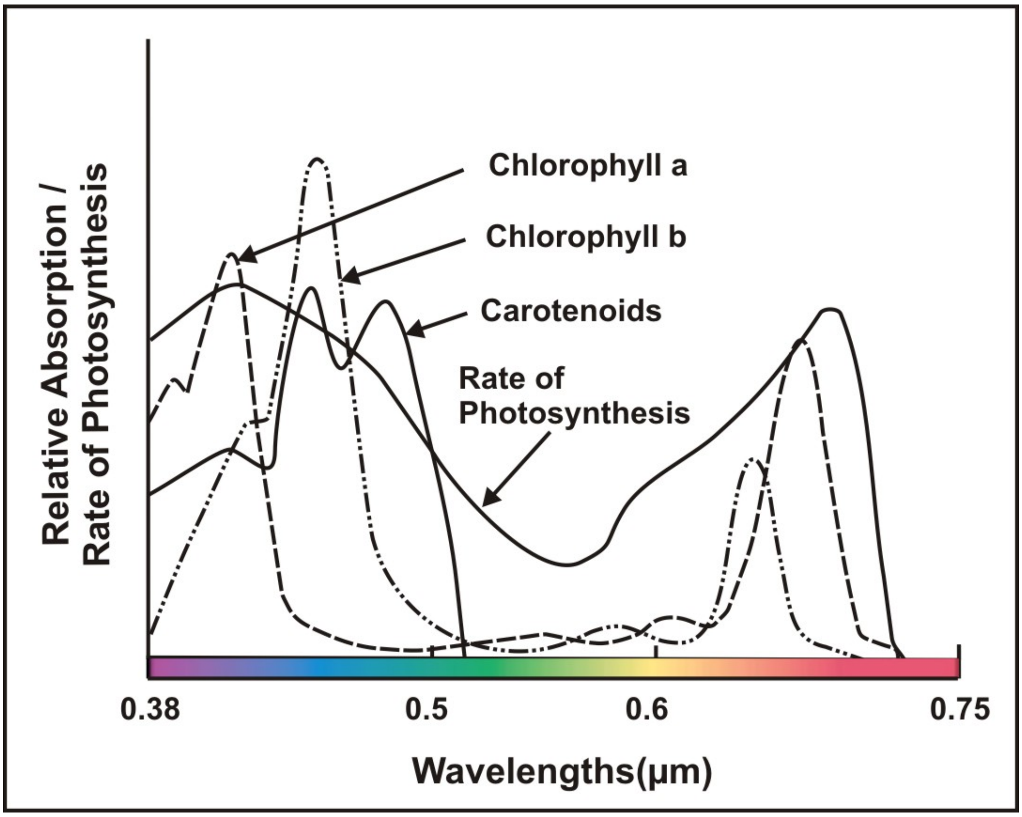

Figure 2.3: Typical absorbance spectra of components, chlorophyll a, chlorophyll b and caretonaids (carotenes). Notice that it is large for blue [0.4 to 0.5 microns] and red [0.65 to 0.7 microns] colors for the chlorophylls and closer to green for cartenoids. The rate of photosynthesis has broad peaks and valleys similar to Chlorophyll and so indicating that chlorophyll contributes to photosynthesis.

or more ingredients for photosynthesis, light, water, and carbon dioxide are reduced or absent photosynthesis decays or stops. If any factor is absent for a long period of time, a plant will die. Because of the molecular structure of chlorophyll, the absorption in the red and blue region of light is high as seen in Figure 2.3. Therefore, when white light is incident, red and blue light will be absorbed and the other colors will be transmitted or reflected. The colors that are left over are perceived by the human eye as green. Chlorophyll masks other pigment colors. Anthocyanins, in turn, mask carotenoids. As summer moves into autumn, decreasing light level causes chlorophyll production to slow. However, the decomposition rate of chlorophyll remains constant, so the green color will fade from the leaves. At the same time, anthocyanin production in leaves increases, in response to surging sugar concentrations. Leaves containing primarily anthocyanins will appear red. Leaves with good amounts of both anthocyanins and carotenoids will appear orange. Leaves with carotenes but little or no anthocyanins will appear yellow. In the absence of these pigments, other plant chemicals also can affect leaf color. An example is tannin, which is responsible for the brownish color of some oak leaves. It is the same range of chemicals that are used to create multiple attractive colors on flowers as well. With age or due to stress of non-availability of water, chlorophyll may break down and in this case, the pigments present in the leaf or flower will reflect the pigments that are still present in them.

The biochemistry of photosynthesis is a very complex. It takes place as two connected but separate reaction pathways - light dependent and light independent and occurs in 3 stages.

1 Capturing energy from sunlight which excites the electrons in chlorophyll molecule to higher energy levels to be moved around and trapped by "electron acceptor molecules"

2 Using the energy to make ATP and reduce $NADP^+$ to NADPH. This is a light dependent reaction

3 Using the ATP and NADPH to synthesize organic molecules (glucose) from CO_2. This is a light independent reaction. This reaction set is termed Calvin-Benson cycle.

In the above description of biochemical reactions, NADPH comes from NADP (Nicotinamide Adenine Dinucleotide Phosphate) which can be reversibly reduced by adding 2 hydrogen ions. It's main function is to transfer hydrogen between molecules [NADPH has a role even in human body functions. It stimulates the body's ability to fight off invading microorganisms such as bacteria by turning O_2 molecules into super oxygen ions, which react with the invading microorganisms and neutralize them]. The experiments conducted to trace the reaction pathways of CO_2 by Prof. Melvin Calvin (for which he was awarded the Nobel prize) are interesting. C^{14} is a radioactive isotope of carbon. It is exposed for a brief period to a green plant that is involved in photosynthesis (in the presence of sunlight). Immediately after exposure to $C^{14}O_2$, the plant's photosynthetic tissue is killed by immersing it in boiling alcohol; this leads to the cessation of all the biochemical reactions. The chemical compounds in the dead tissue are extracted and examined to determine which of them possesses the C^{14}. Following the briefest exposure, the only chemical compound that appeared to possess C^{14} was PGA (phosphoglyceric acid, a three carbon molecule). Following longer periods of exposure, much of the C^{14} was found in a variety of compounds including glucose. By varying the length of the exposure period it was possible to identify the sequence of the reactions leading to glucose.

The separate processes are connected as shown in the block diagram (see Figure 2.4) The key reaction driver is the breaking up of water molecules into protons, electrons, and oxygen enzyme-catalyzed inside the thylakoid area.

$$2H_2O \longrightarrow 4H^+ + 4e^- + O_2$$

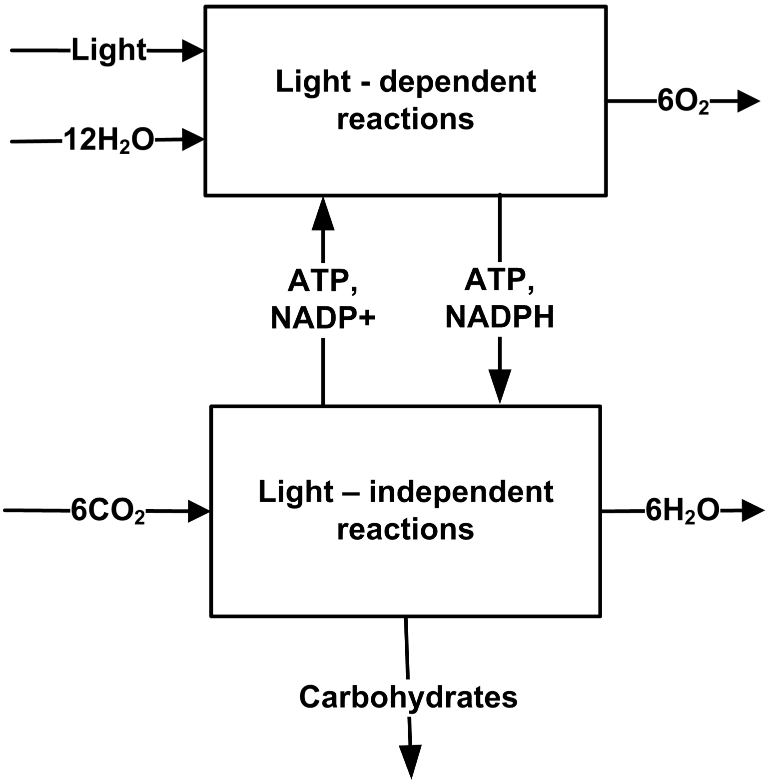

Figure 2.4: The two connected but separate conversion process - light-dependent and light-independent

Oxygen moves out of the system and is released into the atmosphere. The hydrogen ion collection inside the thylakoid helps the production of an important biochemical, namely, adenosine triphosphate (ATP), the precursor for which is already in the thylikoid membrane. The electrons get transported around in the energy enhancement processes. The CO_2 fixation proceeds by its acquisition from the atmosphere and a reaction that attaches itself to a 5-carbon biochemical molecule called RuBP catalyzed by a protein called RUBISCO. This results in a 6-carbon molecule that splits into two 3-carbon molecules, called G3P which is essentially glyceraldehyde-3-phosphate. The hydrocarbon skeleton of G3P can form, glucose, fructose, sucrose, starch and cellulose (see Figure 2.6). Cellulose is a long polymer of glucose (about 1500 units). Typical chemical structure of cellulose is shown in Figure 2.5. The cellulose chains get deposited along the cell walls to produce a fibrous structure. The 3-carbon molecule described above (G3P) is responsible for this pathway being called C3 pathway. G3P is also responsible for the production of other amino-acids and fatty acids. The overall equation of photosynthesis will become

$$\begin{gathered} 6CO_2 + 12H_2O + 18ATP + 12NADPH \rightarrow \\ C_6H_{12}0_6 + 18ADP + 18P_i + 12NADP^+ + 12H^+ + 60_2 \end{gathered}$$

Where P_i represents an inorganic phosphate. This reaction can be stated in a simpler way as

$$\begin{gathered} \text{Carbon dioxide + Water + Sunlight} \longrightarrow \text{Sugar + Oxygen} \\ 6CO_2 + 6H_20 + h\nu \longrightarrow C_6H_{12}0_6 + 60_2 \end{gathered}$$

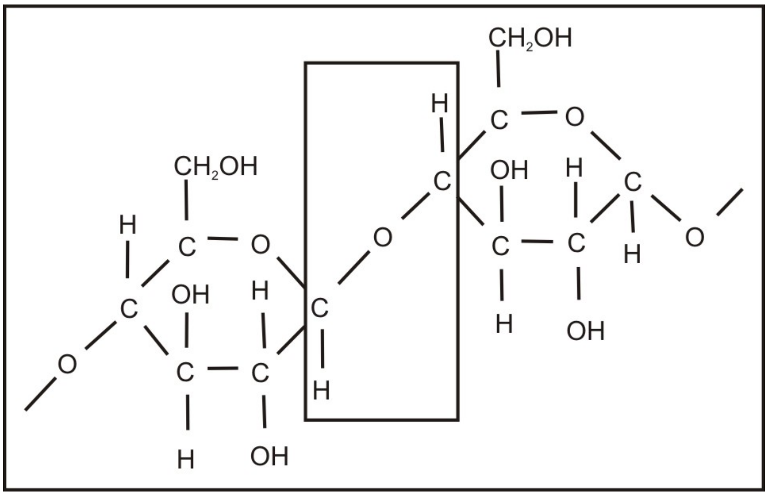

Figure 2.5: The chemical structure of cellulose. This structure gets repeated more than a thousand times to get a cellulose fragment

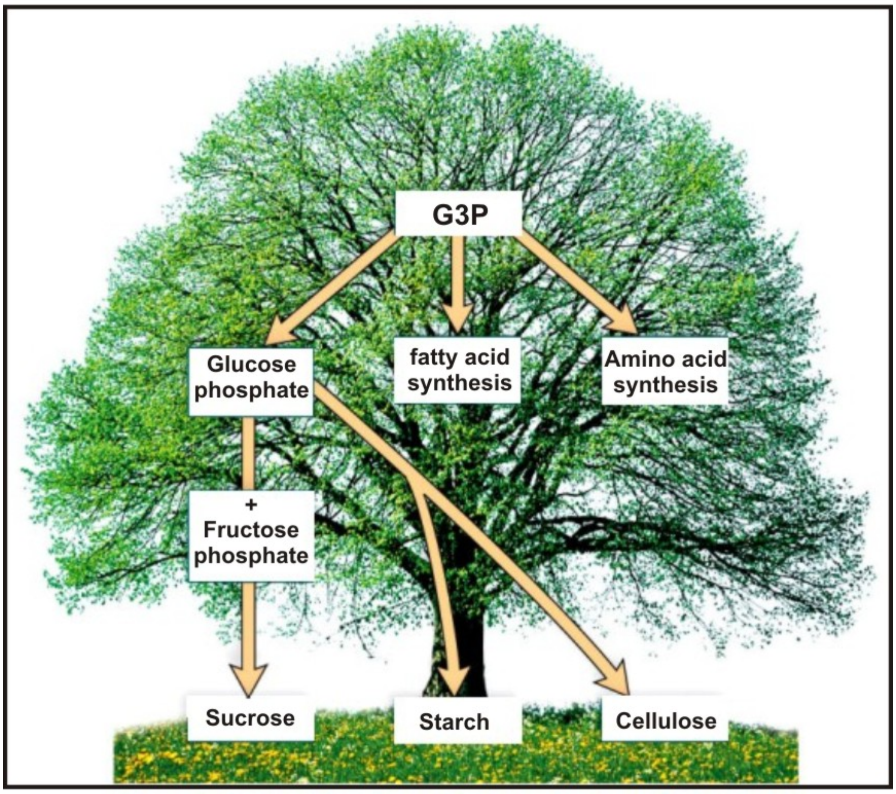

Figure 2.6: Schematic of the plant growth processes

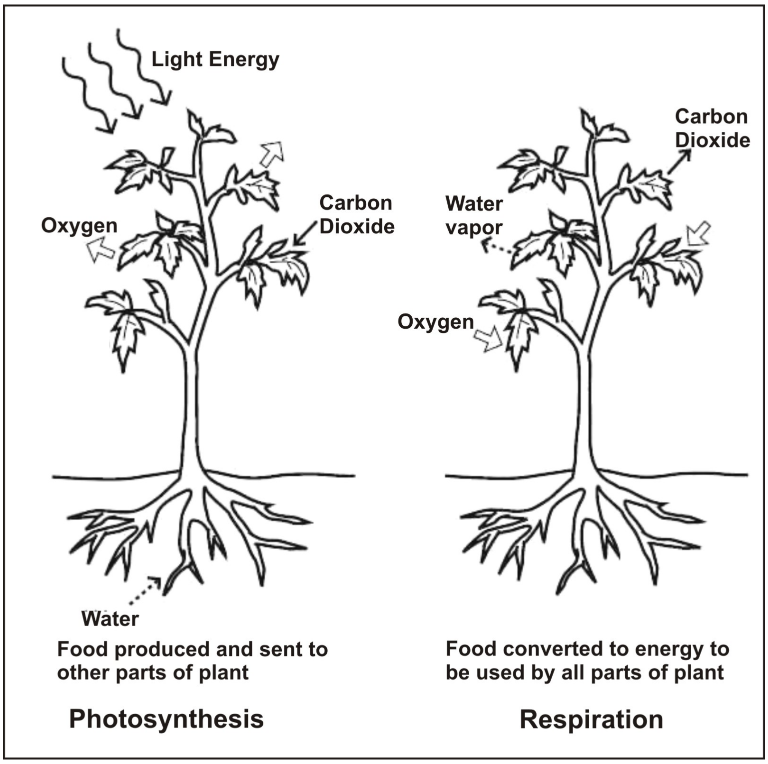

Figure 2.7: Schematic of the photosynthesis and respiration in plants

2.3.2 Respiration and Transpiration

Carbohydrates made during photosynthesis are of value to a plant when they are converted to energy. This energy is used for cell growth and building new tissues. The chemical process by which sugars and starches are converted to energy is called *oxidation* and is similar to the burning of wood or coal to produce heat. Controlled oxidation in a living cell is called respiration and is presented by

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

This equation is essentially the opposite of photosynthesis. Photosynthesis is a building process, while respiration is a breaking-down process. The differences between the two are presented in Table 2.2. Figure 2.7 provides a graphic picture of the processes of photosynthesis and transpiration - the day and night behavior of plants. Respiration occurs in all life forms and in all cells. When a leaf's guard cells shrink, its stomata open up and water is lost. This process is called transpiration. In turn, more water is pulled through the plant from the roots. The rate of transpiration accounts for only 1 % of a leaf's surface but 90 % of the water transpired. The other 10 % is used in chemical reactions and in plant tissues.

Transpiration is responsible for several things:

(a) Transporting minerals from the soil throughout the plant.

(b) Cooling the plant through evaporation.

(c) Moving sugars and plant chemicals.

Table 2.2: A comparison between photosynthesis and respiration

Item	Photosynthesis	Respiration
Food is	produced	used
Energy is	stored	released
Water is	used	produced
CO_2 is	used	produced
O_2 is	produced	used
Light is	needed	not needed

(d) Maintaining turgor (cell) pressure (the pressure exerted by the fluids in a plant cell. This pressure gives added rigidity to plant cells. Cells with a low turgor pressure will be limp or wilted).

The amount and rate of water loss depends on factors such as temperature, humidity, and wind or air movement. Transpiration often is greatest in hot, dry (low relative humidity), and windy weather.

2.3.3 The net effect

In order for a plant to grow and develop properly, it must balance photosynthesis, respiration, and transpiration. Left to themselves, plants have learnt to manage the intricate balance. If a plant photosynthesizes at a high rate, but its respiration rate is not high enough to break down the photosynthates produced, photosynthesis will either slow down or stop. On the other hand, if respiration is more rapid than photosynthesis, the plant will not have adequate photosynthates to produce energy for growth. Hence, growth either will slow down or stop altogether.

When stomata are open, transpiration occurs, sometimes at a very high rate. A small plant may transpire 200 liters of water per season, but a large tree may move 350 liters per day! Plants have problems if they lose too much water, so stomata close during hot, dry periods when transpiration is highest. However, CO_2, which is needed for photosynthesis, also enters the plant through open stomata. Thus, if stomata stay closed a long time to stop water loss, not enough CO_2 will enter for photosynthesis. As a result, photosynthesis and respiration will slow down, in turn reducing plant growth.

Many herb plants produce lots of high-energy oils, which help them survive in the dry landscapes where they evolved. These oils help them survive extended periods of the closure of stomata.

2.4 C3, C4 and CAM plants

The plants that follow the pathway described earlier are called C3 plants. There are also plants that follow different pathways called C4 and CAM plants. The features of all these plants are summarized below (see internet sites, in particular internet-5, (2010)).

1. C3 plants

The process is more efficient than C4 and CAM plants under cool and moist conditions and under normal light because requires less machinery (fewer enzymes and no specialized anatomy).

Most of the plants (95 %) are C3 in nature. They include Trees, wheat, rice, barley, oats, potatoes, sugar beet, soya beans, sweet potatoes, cassava, bananas, coconuts, chickpeas, cotton, roses, strawberries, most fruits and vegetables.

2. C4 plants

It is called C4 because the CO_2 is first incorporated into a 4-carbon compound. This pathway photosynthesizes faster than C3 plants under high light intensity and high temperatures. It has better water use efficiency.

C4 plants include several thousand species in at least 19 plant families. They include maize, cane Sugar, millet and sorghum, and grasses.

3. CAM plants (Crassulacean Acid Metabolism)

They are called CAM after the plant family in which it was first found (Crassulaceae) and because the CO_2 is stored in the form of an acid before use in photosynthesis. It has better water use efficiency than C3 plants under arid conditions due to opening stomata at night when transpiration rates are lower (no sunlight, lower temperatures, lower wind speeds, etc.). When conditions are extremely arid, CAM plants manage to be somewhat like a perpetual energy machine, but there are costs associated with running the machinery for respiration and photosynthesis. But this idling does allow the plant to survive dry spells, and it allows the plant to recover very quickly when water is available again (unlike plants that drop their leaves and twigs and go dormant during dry spells).

CAM plants include many desert-related plants like cactuses and agaves and also some orchids.

How good the plant is at bringing in carbon dioxide for photosynthesis without losing much water out of its stomata is characterized by a quantity called water use efficiency. It is the ratio of carbon dioxide intake to water lost through transpiration. A comparison of the water use efficiency measured in terms of g/water lost per g CO_2 fixed is 500 to 1000 for C3 plants, 200 to 350 for C4 plants and 50 to 100 for CAM plants.

2.5 Photosynthetic efficiency

The solar energy received from sun is shown in Fig. 2.8. There are two aspects - the spectrum measured outside of earth's atmosphere and the spectrum on the surface of the earth. The radiation that passes through the atmosphere before reaching the earth's surface interacts with it in various modes - absorption, transmission and re-radiation all of which are wavelength dependent. This is also clear in Fig. 2.8. Both CO_2 and H_2O are principal absorbers and radiators in the atmosphere in the infrared range. It is the absorption of the radiation from the earth (that occurs at 300 K) that leads to the green house gas effect and the current problem of global climate change arises out of the absorption by CO_2 largely (even though, other gases like NO_2, and CH_4 also contribute to this problem).

If we integrate the variation over all the wave lengths, we get the power received per unit area in the space just outside the atmosphere. This called the solar constant and its value is 1,370 W/m^2. This value varies by 6 % up to a maximum of 1450 W/m^2.

What would be of interest for photosynthesis would be the visible range - 0.38 to 0.7 μm. The energy integrated over this wave length is about half of the total energy. This energy is called photosynthetically active radiation (PAR). If we account for losses in the atmosphere (45 - 50

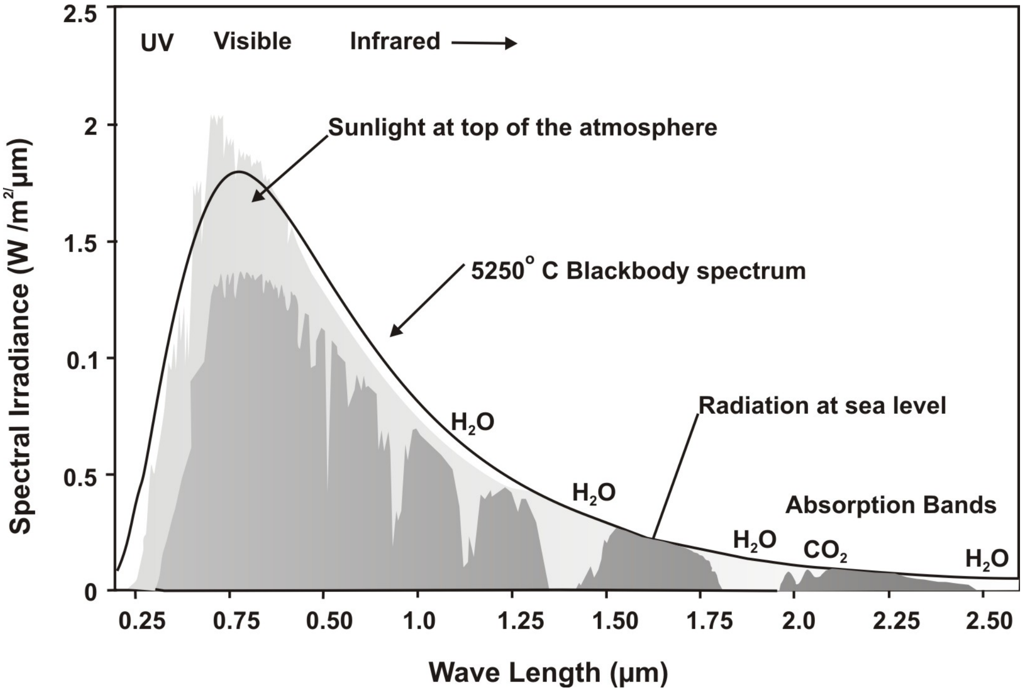

Figure 2.8: The solar spectrum. Notice the differences between that received in outer space and on the surface of the earth (drawn from Wiki-sunlight, 2010)

%), the PAR that will be available on a flat surface at earth's radius will be 25 - 28 % of the total radiation. This then amounts to 340 to 390 W/m^2. Since earth is spherical, a flat surface at equator will be about the same as the surface area of earth in that region. However as one moves to higher latitudes, the actual surface area of the earth is far more than the flat area. This reduces the flux over the surface at higher latitudes. Further, along the path of light, the atmospheric layer thickness is the smallest at equator and increases towards the pole. This reduces the flux of energy received at higher latitudes. The absorption by the atmosphere is a strong function of the clouds and rain both of which vary strongly over the globe. Therefore it may turn out that the absorption is strong near the equatorial region at a time when the sky is clear at higher lattitudes. Thus the amount of energy received in a given area (called insolation) is a strong function of area under consideration and time. It is measured over various parts as a function of time and the data used as an input for design. A typical distribution If we take these factors into account, the peak PAR received in India varies between 400 to 600 W/m^2. Measuring the PAR distribution over a given surface is a complex task discussed in Pinker and Laszlo (1991). Satellite data and atmospheric modeling are required with validation over a number of selected areas before such maps are produced. The PAR distribution over the globe averaged over an year is shown in Fig. 2.9. The regions of the sea in the equatorial region seem to receive far more radiation than the land mass. It must also be recognized that at every location, the solar radiation builds up from sunrise and comes down at sunset. If we integrate the variation over a day, one gets the energy over the day as 12 to 24 MJ throughout the entire year. Thus what matters for the plant productivity is the energy captured on a day-to-day basis through the plant growth period. Agricultural crops have different time durations from sowing to harvest.

A fundamental approach to calculating photosynthetic efficiency has been examined [see for instance, Bolton and Hall, 1991]. It is known that it takes an average of eight photons of light to "fix" each molecule of CO_2, and with a mean energy of 217.4 kJ/mole for each photon, and a

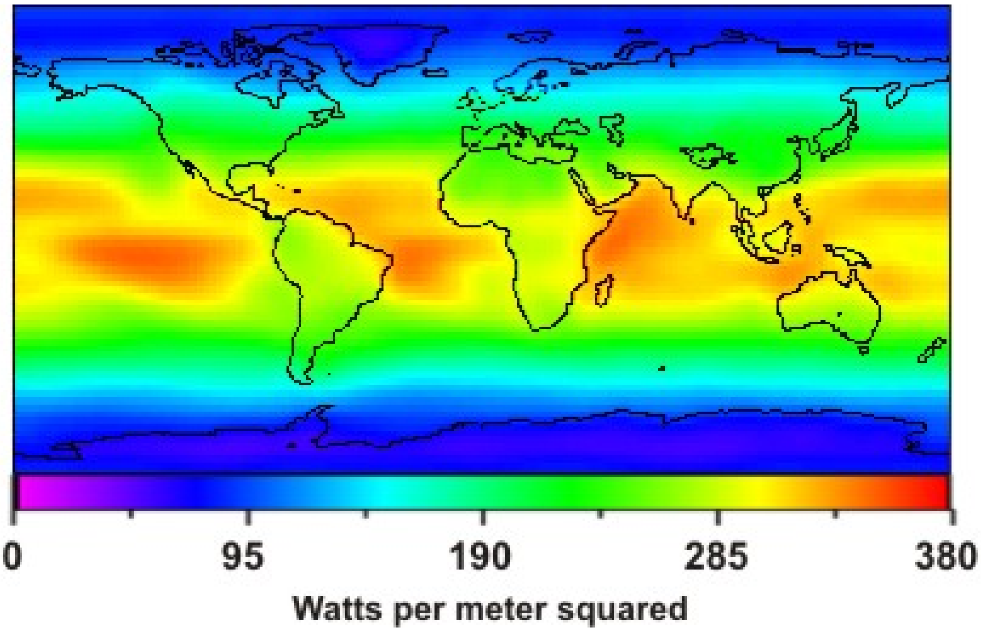

Figure 2.9: The distribition of photosynthetically active radiation (PAR) averaged over an year over the planet

mean enthalpy (heat) of combustion for a glucose molecule, CH_2O of 467 kJ/mole (obtained as one sixth of the heat of combustion of glucose, $C_6H_{12}O_6$, an hexamer of CH_2O = 2.8 MJ/mole), the process efficiency is deduced as (467 × 100)/(8 × 217.4) = 27 %. Since the number of photons in the PAR constitutes about 45 - 47 % an overall photosynthetic efficiency of (45 - 47) % × 27 % = 12.7 % can be expected as an absolute maximum. Further deficiencies out of differential absorption of photons in different spectral bands will only reduce the efficiency from this absolute maximum. Also, there is energy required for translocation and respiration that amounts to about 33 % of the total value and in a plant or tree cover, the presence of a "canopy" limits the available light to about 80 %, so we might expect nearer to 12.7 % × 67 % × 80 % = 6.8 %, which is the commonly quoted mean. In reality this varies significantly, and with sugarcane it turns out to be around 8 % whereas some plants may be as low as 0.1 %, while for most crop plants, 1 -2 % is typical. Interestingly, there is a paradox of photosynthesis that relates to the fact that in dim light the rate of photosynthesis is low but efficiency is high and conversely, in direct sunlight the rate of photosynthesis is high but efficiency is low.

A simple estimate can be made based on the productivity of biomass. Sugarcane is known to be the highest in terms of capturing solar energy. The maximum measured output of sugarcane is about 120 t/ha per crop which is harvested about 140 days after planting. It is understood that all agronomic properties are under optimal conditions for this productivity to be achieved. If we take the moisture level of 60 % at the time of harvest, productivity translates to about 60 tonnes of sun-dry biomass (10 %) moisture. The calorific value of the sun-dry biomass is about 16 MJ/kg. This implies the energy captured as $60 \times 10^3 \times 16 \times / (140 \times 10^4 \times 0.5) \sim$ 1.37 $MJ/m^2/day$. The value 0.5 used in the above expression refers to the fact that sunlight is available only for half the day. If the photosynthetic efficiency is taken as 8 % as indicated earlier, the average solar energy incident will be 1.37/(0.08) = 17 $MJ/m^2/day$. The measured solar insolation varies between 12 to 24 $MJ/m^2/day$ in India. Thus, these data appear consistent.

On the above basis, the efficiency of dry matter produced by photosynthesis is about 2 - 3 % for rice and wheat and 3 to 4 % for maize. There is a difference of about 1.5 % in the photosynthetic efficiency between C3 and C4 plants because the respiration losses in C3 plants are higher by this amount in comparison to C4 plants. Rice (C3 plant) is a very important crop for a large population of the world and much effort is going on to raise its yield (see Sheehy et al, 1999). It is estimated that if genetic engineering is used to grow rice with C4 photosynthesis that has the radiation conversion efficiency of maize, a 50 % increase in yield is considered conceivable.

In summary, achieving growth rate is affected by the optimal light, ambient temperatures, the availability of water and nutrients, the surface to volume ratios of the plant material, pH, stocking density and the concentration of carbon dioxide. Estimates of photosynthetic efficiency in forests has been provided by Hellmers (1964). A more fundamental exploration of photosynthesis has been presented by Wassink (1959) and Zhu et al (2008).

2.6 Other chemical-structural components of a plant

Apart from cellulose that is formed from glucose, two other major components that are produced by the plant system are, hemicellulose and lignin. Also certain proteins, called crude proteins and extractives that can be extracted by using a solvent are produced by the plant.

Hemi-cellulose consists of short, highly branched chains of sugars (molecular weight 50 to 200 times the basic unit). In contrast to cellulose, which is a polymer of only glucose, hemicellulose is a polymer of five different sugars, (the five-carbon sugars, usually D-xylose and L-arabinose and six-carbon sugars, D-galactose, D-glucose, and D-mannose) and uronic acid. The sugars are substituted with acetic acid. The branched nature of hemi-cellulose renders it amorphous and relatively easy to hydrolyze to its constituent sugars compared to cellulose. When hydrolyzed, the hemi-cellulose from hardwoods releases products high in xylose, a five-carbon sugar. The hemi-cellulose found in softwoods, by contrast, yields more six-carbon sugars. A combination of cellulose and hemi-cellulose is called holo-cellulose.

Lignin is the most abundant organic polymer next only to cellulose that is a non-carbohydrate, poly-phenolic structural constituent of wood and other plant material that encrusts the cell walls and cements the cells together. It has a highly complex, cross-linked *aromatic* structure of molecular weight about 10,000 derived principally from coniferyl alcohol ($C_{10}H_{12}O_3$) by extensive condensation polymerization. It is unusual because of its heterogeneity and lack of a defined primary structure. Lignin fills the spaces in the cell wall between cellulose, hemicellulose, and other components. It is covalently linked to hemicellulose conferring mechanical strength to the cell wall and to the plant as a whole. The actual biochemistry of its production in the plants is so complex that it still remains to be uncovered (even after a hundred years of research).

Lignin plays a crucial part in conducting water in plant stems. The polysaccharide components of plant cell walls are highly hydrophilic and thus permeable to water, whereas lignin is more hydrophobic. The cross-linking of polysaccharides by lignin is an obstacle for water absorption to the cell wall. Thus, lignin makes it possible for the plant's tissues to conduct water efficiently. It is one of the most slowly decomposing components of dead vegetation, contributing a major fraction of the material that becomes *humus* as it decomposes (Wiki-humus, 2010). The resulting soil humus generally increases the photosynthetic productivity of plant communities growing on a site as the site transitions from disturbed mineral soil through helping moisture retention under varying weather conditions. Highly lignified wood is durable and therefore a good raw material for many applications. Figure 2.10 shows the cross section of a plant explicitly bringing out the cellular structure. The long grains are essentially cellulosic (some

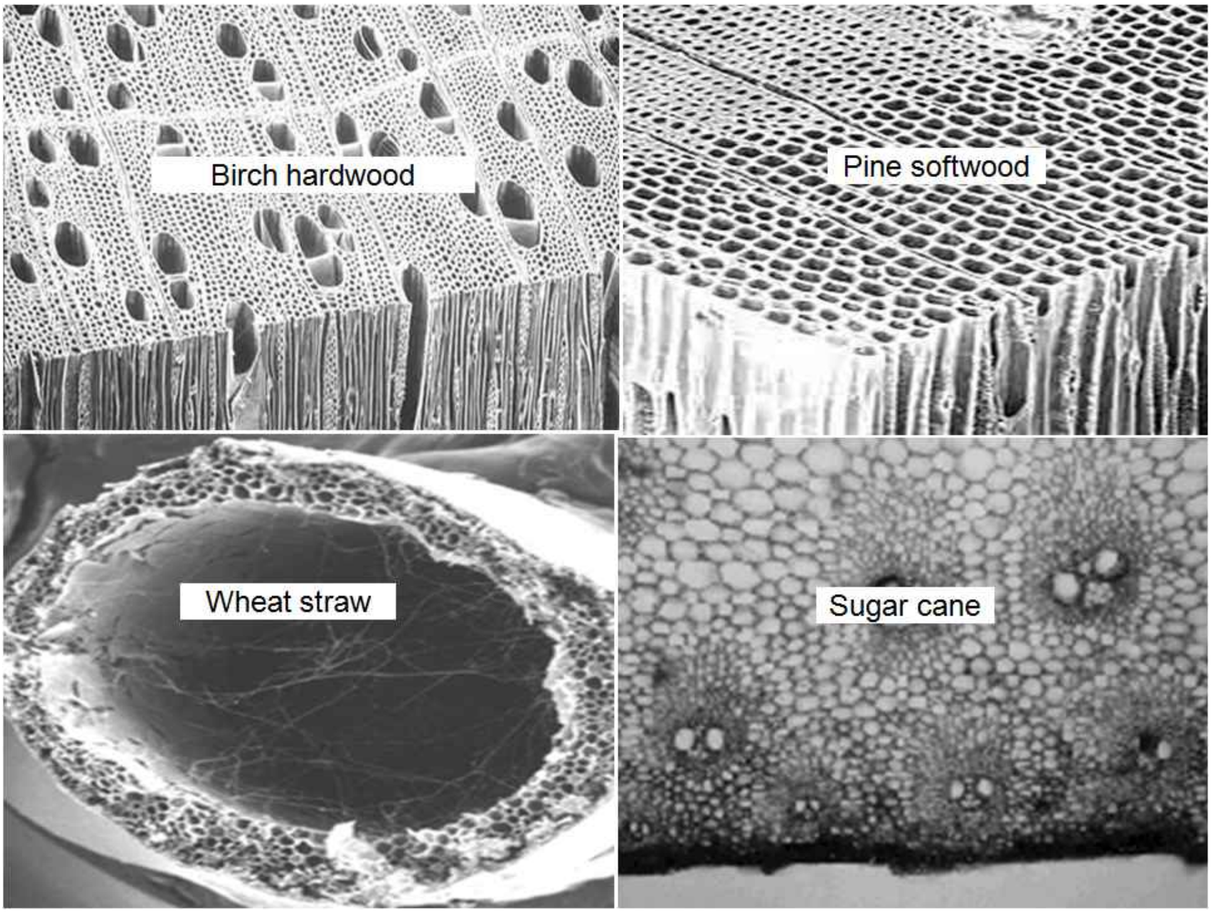

Figure 2.10: The cross section of various plant materials. An ordered growth pattern can be seen in all of them

random fibers of hemicellulose are also embedded in the structure). The matrix is of lignin. The way the three principal components are broadly located in the plant is shown in Figure 2.11. Apart from cellulose, hemi-cellulose and lignin that are in large fractions, plant material also produces and stores resins, fatty acids, and oils. Inorganic elements namely, magnesium, potassium, calcium, iron, phosphorous and a few others are also present in the plant structure. These elements have special functions.

Magnesium is the basic core element of chlorophyll. In a way it is the basis of all green life. *Potassium* is present mostly in growing regions. It helps to synthesize the carbohydrates and proteins. In its absence leaves lose their colour and gradually wither away. *Calcium* occurs in the cell walls. It promotes the growth of plant. In its absence plant becomes stunted. *Iron* is present in protoplasm and chlorophyll is not formed in its absence. *Nitrogen* is essential for growth. In its absence leaves become yellowish. It is important constituent of protein, chlorophyll, and protoplasm.

Nitrogen excepting, other elements form oxides when biomass is involved in combustion and this material is left behind as ash. The ash content of biomass varies from about 0.5 % for some woods to as high as 20 % as in rice husk and rice straw. Acquatic plants have even higher amount of ash ($\sim$ 25 %)

The composition of biomass (on an ash-free basis) when it is broken down to structural fragments is shown in Table 2.3 for several species. Most of the structural components vary sig-

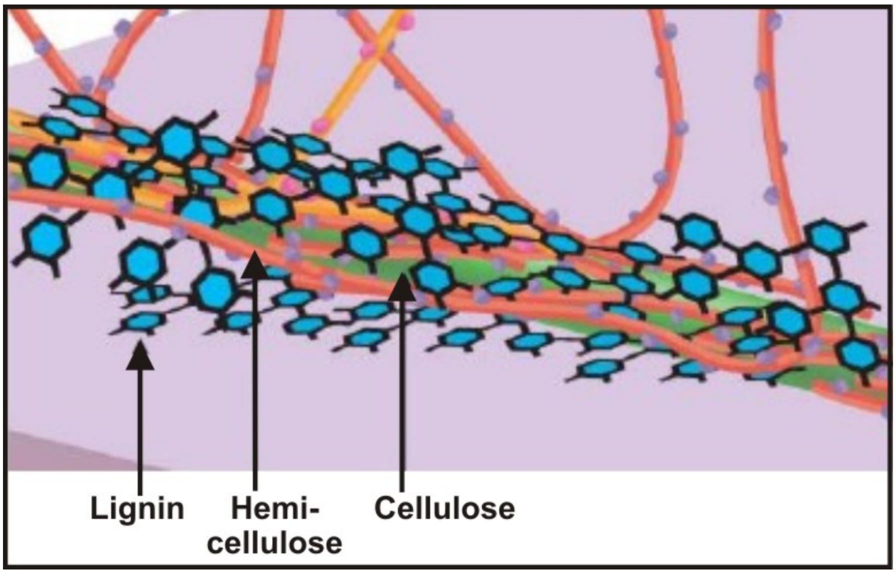

Figure 2.11: Schematic of the plant growth processes

Table 2.3: Structural composition of various biomass, CP = Crude Protein

Species	Cellulose %	Hemi-cellulose %	Lignin %	Extractives CP + oil,etc, %	Ash %
Eucalyptus -1	45.0	19.2	31.3	3.8	0.7
Eucalyptus -2	50.0	7.6	38.8	3.6	0.6
Pine	40.0	28.5	27.7	3.5	0.3
Soybean	33.0	14.0	14.0	5.0	6.0
Bagasse	41.3	23.8	18.3	13.7	2.9
Coconut coir	47.7	26.9	17.8	6.8	0.8
Coconut shell	36.3	25.0	28.7	9.3	0.7
Coir pith	28.6	17.3	31.2	15.8	7.1
Corn cob	40.3	26.9	16.6	15.4	0.8
Corn stalks	42.7	23.6	17.5	9.8	6.4
Cotton gin waste	77.8	16.0	0	1.1	5.1
Groundnut shell	35.7	18.7	30.2	10.3	5.1
Millet husk	33.3	26.9	14.0	10.8	15.0
Rice husk	31.3	24.3	14.3	8.4	21.7

nificantly; however, low ash containing biomass like wood has about 50 % of cellulose, 25 % hemi-cellulose and the rest lignin and extractives. The word extractives refers to substances that can be extracted by using a solvent. These constitute crude protein, oils, starch and sugar in varying amounts. Table 2.4 shows the molecular formula of each of the components that were discussed above. An equivalent molecular formula for coconut shell and Eucalyptus wood with the composition drawn from Table 2.3 ia also shown. As can be seen from Table 2.4, hemi-cellulose has the highest hydrogen and oxygen fraction; next follows cellulose and then lignin. These data are set out classically in a diagram of H/C vs. O/C as in Fig. 2.12. This plot was set out by van Krevelen (1993) to describe the evolution of fossil fuels from biomass (due to geological changes over millions of years). The natural formation of peat, lignite, coal (and anthracite coal as the final form) is clear from the progressive reduction of oxygen and hydrogen due to the generation of volatiles (because of high pressure and temperature). The calorific value per unit

Table 2.4: The molecular formulae of structural parts of biomass

Component	Formula	H:C	O:C
Cellulose	$C(H_2O)_{0.833}$	1.66	0.833
Hemi-cellulose	CH_2O	2.0	1.0
Lignin (1)	$CH_{1.3}O_{0.3}$	1.3	0.3
Lignin (2)	$CH_{1.2}O_{0.38}$	1.2	0.38
Extractives (crude protein)	$CH_2O_{0.5}\ N_{0.3}$	2.0	0.5
Coconut shell (36:25:30:9)	$CH_{1.64}\ O_{0.71}\ N_{0.0027}$	1.64	0.71
Eucalyptus (50:25:20:5)	$CH_{1.6}\ O_{0.71}\ N_{0.0015}$	1.6	0.71

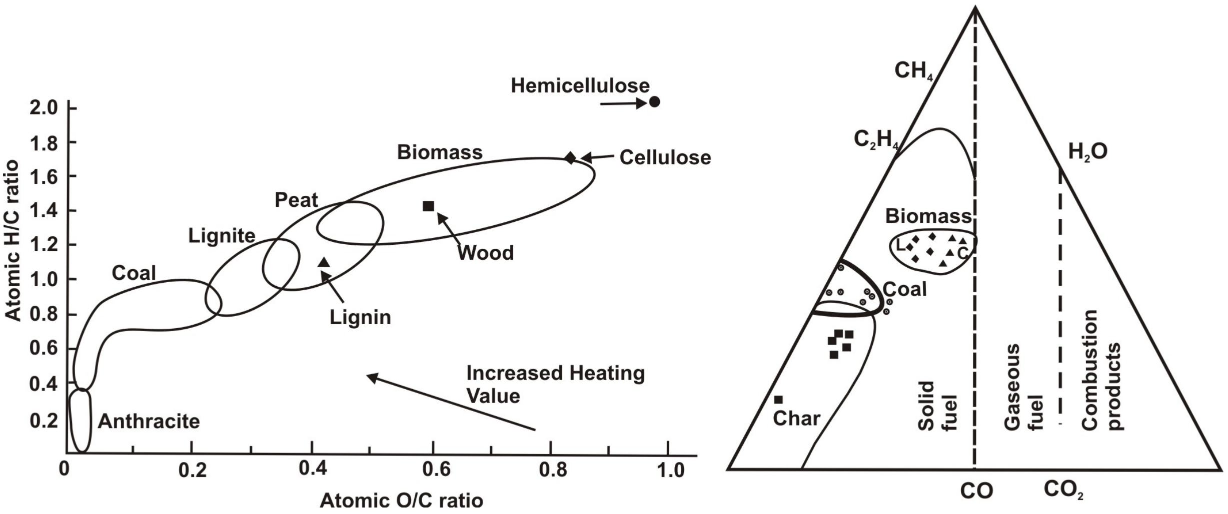

Figure 2.12: The plot of H/C with O/C of various structural parts of wood, along with those of peat and coal in van Krevelan plot and Ternary diagram.

mass also increases along this path. A point that is not obvious in the diagram is that the ash content that is about a few percent for woody biomass increases as one proceeds towards coal. This is because of the environment in which caol gets formed. While the best coals have about 5 % ash, Indian coals have ash as much as 45 %. There is an alternate way of presenting the information called the ternary diagram. This is also shown on the right side of the plot.

It is the crude protein as a part of extractives that contributes nitrogen to biomass. The fraction of crude protein varies up to 16 % and hence the nitrogen mass fraction in biomass goes up to 2.5 %. Since the fraction of various components is not the same in all the plants as is clear from Table 2.3, the C:H:N:O composition of biomass will be different. What more, the composition may be *different for the same species depending on the age and the location where it is grown* [Lee et al, 2007]. This is because the growth processes can be altered by the availability of nutrients and water, different amounts at different stages of growth. Hence there could be minor variations of these elements in the plant (Eucalyptus- 1 and Eucalyptus - 2 are shown as examples here).

2.7 Bio-residues for power generation

The bio-residues are derived from plantations, agricultural operations as well as urban solid waste.

Plantations are grown for timber stock as well as poles to be used for scaffolding in building construction. Typically after five years or so, when the tree stock is sufficiently big, the plantation is harvested. The stock will go to the market with or without bark – each has specific use. The lops and tops that are usually considered as wastes constitute about 30 % of the tree. There are also energy plantations that are grown specifically for the purpose of power generation. It is the economics that drives investments into plantations and the choice of the product for energy purposes – the whole tree or lops and tops. When the plantations are operated in a manner that productivity is just more than for use, this option becomes *renewable*.

Agricultural operations occupy an important role in developing countries, particularly, India. Of the 328 mha of the total land mass, 141 mha of land is the net area sown and the gross cropped area is 191 mha (implying that 50 mha is double crop area). Out of the net sown area, only 55 mha is irrigated and the rest, 86 mha is rain-fed. Around 50 % of the food crops and 68 % of the non-food crops are grown in rain-fed areas. In addition, the average land holding is about 0.4 ha and the land is held by small farmers. Both these aspects are impediments to achieving higher productivity from the land. Despite these drawbacks, India ranks second worldwide in farm output. Agriculture accounts for 14 to 16 % of the Gross Domestic Product (GDP), employing more than 60 % of the total workforce and plays a significant role in the overall socio-economic condition in India. It is the largest producer in the world of milk, cashew nuts, coconuts, tea, ginger, turmeric and black pepper. It also has the world's largest population (281 million) involved in farming. It is the second largest producer of wheat, rice, sugar and groundnut. Other major crops include coarse cereals, pulses and oilseeds. Cereal crops or grains are mostly grasses cultivated for their edible grains or a fruit seeds. Cereal grains provide more energy worldwide than any other type of crop and are therefore staple crops. They are also a rich source of carbohydrate.

On the other hand, pulses are defined as annual leguminous crops yielding from one to twelve grains or seeds of variable size, shape and color within a pod, by the Food and Agricultural Organization (FAO of UNO). They have high protein and essential amino acid content. Millets are also small-seeded species of cereal crops or grams.

Table 2.5: Crops and the season

Season	Crops
All seasons	Paddy, jowar, bajra, cotton, arhar, banana, coconut, groundnut, arecanut, mango, rubber, coffee, horsegram cashewnut, cardamom, blackpepper, other plantation trees
Kharif only; July to Dec	Meshta, moth, avare, barseem, castor seed, cowgram, kodo millets, korra
Rabi only; Jan. to June	Wheat, barley, cuminseed, safflower, isabgol, kulthi,teora, kesar

There are two major cropping seasons in India, namely, kharif and rabi. The terms kharif and Rabi are derived from Arabic and mean the seasons "autumn" and "spring". The kharif season is during the south-west monsoon (July-October). During this season, agricultural activities take place both in rain-fed areas and irrigated areas. The Rabi season is during the winter months, when agricultural activities take place only in the irrigated areas.

Table 2.5 shows the crops grown in various seasons. Kharif (variously spelt including as Khariff) season would generally cover months of summer and rains (sown during some time between April to July, and harvested by October to December). Most important Kharif crop is paddy. Rabi crops are generally sown between October to February and harvested by June. Most important Rabi crop is wheat. With the expansion of irrigation and green revolution, traditional pattern of cultivation has changed in India. Even so, paddy and wheat remain the major Kharif and Rabi crops respectively. Other Kharif crops include sugarcane, groundnuts, maize, and a variety of pulses. Other Rabi crops include barley and a variety of oil seeds.

Table 2.6 and 2.8 carry information about the agricultural output of India obtained from several sources, largely related to the Ministry of Agriculture, Government of India published on their website. The data is classified into cereals and millets, pulses, oil grains, and other crops including cash crops. The table is set out under different heads: cereal crops/millets, pulses, oil crops and others that include cash crops also. Some crops come under more than one head; for example, cotton can appear under oil as well because it gives cotton seed oil and coconut can appear in cash crops included under other crops. This is due to multiple outputs from the same crop. The photosynthetic efficiency is described by the productivity (t/ha). Several of these productivities are smaller than internationally achieved values; for instance, the best paddy output has been paddy at 10 t/ha in Egypt, wheat at 8 t/ha in the UK, Maize at 9.4 t/ha in Turkey, groundnut at 20 t/ha in Indonesia, sugarcane at 120 t/ha in Egypt. The closest of the best productivities in India is in Sugarcane at 110 t/ha. The key problems for productivity have been brought out earlier – larger fraction of rain-fed cultivation by a very large number of farmers with small land size finding it difficult to do a long term management of agriculture.

In terms of photosynthetic efficiency, sugarcane ranks the highest, potato, tea, banana follow suit. It must be understood that the passive biomass other than the "crop" is included. For potato, and banana they are significantly larger than the "crop" (see later). Stated more precisely, at best outputs, the total "product" of photosynthesis is 50 dry t/ha for sugarcane, 25 to 27 dry t/ha for rice, wheat, groundnut, potato and banana, and 15 dry t/ha for coconut. Using the information in these tables it is possible to derive the information on the residues. There are two parts to this task. The first part of the task relates to identifying the residues and their magnitude. The second part relates to determining the amount that will be available as waste for power generation; this is because the residues have other important uses – fodder for livestock, roofing and other domestic and semi-industrial demands. The magnitude of fodder is very significant since the total size of domesticated animals is close to a billion (NDDB, 2010). To determine the magnitude of residues being used for other societal uses, a study was undertaken on a national scale when more than hundred consultants were involved (under a major program of the Ministry of Non-conventional Energy Sources, now called Ministry of New and Renewable Energy, with the Indian Institute of Science as a focal institution) to generate the data on the agricultural production as well as use. The data on production was cross-checked with that obtained from several sources - Ministry of Agriculture (2010), Department of Pulses (2010), and India statistics (2010]. In addition the data on the crop-to-residue ratio – how much of residue is obtained per unit mass of the "crop" on a dry basis was generated partly from direct experiments and from the work of the consultants. The difference between the waste generated and waste used for other purposes is called surplus and it is this that qualifies for use in energy generation. These data were integrated after verification at several levels into nation-wide maps and tables that can be accessed on the basis of a state, district or taluk under national biomass atlas at *http://cgpl.iisc.ernet.in* for the year 2004. Incremental changes over later periods are currently being worked out. Broadly it appears that the changes in major crops is marginal. Significant changes are expected in oil crops as well as pulses. The wastes from these go largely to fodder (nearly 90 % in many cases). As such the broad availability on a first-cut basis is about the same even at this time of writing.

For most crops the crop-to-residue ratio approach is adequate. For some "tree" crops like, cotton, coconut, arecanut, and coffee, a better strategy would be to obtain the magnitude of residue

Table 2.6: Agricultural crops in India – acreage, productivity and production

Crop		Acres		Productivity		Production	
	Kharif	Rabi	Total		Kharif	Rabi	Total
		—mha–		*—t/ha—*		*—mmt—*	
Cereals and Millets							
Paddy	32.0	9.00	41.0	2 - 3	66.0	24.0	90.0
Wheat		22.0	22.0	2.6 - 3		60.0	60.0
Maize	5.6	0.65	6.25	1.7 - 3	10.0	1.4	11.4
Jowar (grain sorghum)	4.4	4.90	9.3	0.8 - 1.1	5.0	4.4	9.4
Bajra (pearl millet)	8.3	0.03	8.33	0.7 - 0.8	5.9	0.02	5.92
Ragi (finger millet)	1.4		1.4	0.5 - 0.6	0.8		0.8
Barley		0.70	0.7	1.7 - 2.0	1.3		1.3
Total cereals	51.7	37.28	88.98		89.0	89.82	178.82
Grams/Pulses							
Red gram (arhar)	3.50		3.50	0.5 - 0.8	2.70		2.70
Black gram (urad)	2.30	0.65	2.95	0.4 - 0.6	0.90	0.35	1.25
Chana dal (bengalgram)		7.60	7.60	0.7 - 0.9	6.90		6.90
Peas and Beans	0.01	0.77	0.78	0.9 - 1.0	0.71		0.71
Green gram (mung)	2.45	0.67	3.12	0.3 - 0.4	0.68	0.25	0.93
Moth (kidney bean)		1.30	1.30	0.1 - 0.2	0.17		0.17
Masur (lentil)	1.50		1.50	0.6 - 0.7	0.95		0.95
Kultha (horse gram)	0.38	0.27	0.65	0.3 - 0.4	0.16	0.10	0.26
Lathyrus	0.63		0.63	0.5 - 0.7	0.34		0.34
Total pulses	10.77	11.26	22.03	0.3 - 0.7	5.73	8.48	14.21
Oil crops							
Groundnut	5.80	0.80	6.40	0.8 - 1.4	5.50	1.10	6.60
Soyabean	7 .25		7.25	0.9 - 1.1	7.25		7.25
Coconut			1.80			6.0*	6.00
Rape and Mustard		6.27	6.27	0.8 - 1.1		6.67	6.67
Sunflower	0.50	1.56	2.06	0.5 - 0.7	0.30	0.80	1.13
Safflower		0.30	0.30	0.5 - 0.7	0.20		0.20
Castor seed	0.83		0.83	1.1 - 1.4	1.10		1.10
Sesame (til)	1.10		1.10	0.7 - 0.8	0.80		0.80
Cashew	0.80		0.80	0.8 - 1.0	0.70*		0.70
Total oil crops	16.28	7.93		26.81	15.85	14.57	30.42

* Perennial crop, also plantation crop

Table 2.7: Agricultural crops in India – acreage, productivity and production(contd)

Crop	Acres			Productivity	Production		
	Kharif	Rabi	Total		Kharif	Rabi	Total
		-mha-		*—t/ha—*		*-mmt-*	
			Other crops / fruits				
Sugarcane		4.0	4.0	50.0 - 110.0		280.0	280.0
Arecanut		0.26	0.26	0.9 - 1.1		0.26	0.26
Tapioca	0.17	0.04	0.21	24.0 - 27.0	4.1	1.4	5.5
Cotton		8.0	8.0	0.6 - 0.8	5.7		5.7
Jute/Mesta	0.96		0.96	1.8 - 2.2	2.0		2.0
Coffee		0.35	0.35	0.8 - 1.0	0.3*		0.3
Tea		0.57	0.57	15.0 - 20.0	10.7*		10.7
Potato	1.37		1.37	16.0 - 18.0	23.2		23.2
Onion	0.55		0.55	10.0 - 14.0	6.6		6.6
Banana	0.5		0.5	35.0 - 40.0	16.0		16.0
Mango	1.5		1.5	6.0 - 8.0	10.5*		10.5
Other fruits	1.8		1.8	7.0 - 12.0	18.1		18.1
Total	6.85	13.22	20.07		97.2	281.66	378.86
Total (all)	85.60	76.54	162.1		207.58	394.53	602.11

* Perennial crop, also plantation crop

as t/ha directly. These data are presented in Tables 2.6 and 2.8; uncertainties in this table that would be typically of ± 20 %. There are also yearly variations in these data which need to be kept in mind. The properties that affect the use of these residues for thermal applications are their density and ash content. The density of most of the residues is between 50 to 100 kg/m^3 and only for a few residues it is larger. For corn cobs it is about 200 to 250 kg/m^3, cotton stalk about 300 to 400 kg/m^3 and only coconut shell about 1100 kg/m^3. These are intrinsic densities of the materials. When they are loaded, the packed density will be lower - about 10% to 50% of the intrinsic density.

The low density of most of the residues is a serious problem both for transportation and for use in thermo-chemical conversion applications. The best way to obviate this problem would be to densify these materials at locations not far from where they are generated. Once densified into briquettes or pellets, the material qualifies for economic transportation and use. In many European countries, even wood stock is dried, pulverized and then pelletized to high densities - 1100 to 1200 kg/m^3 and marketed largely for use of domestic and district heating applications in winter. In India, multiple residues are collected depending on the availability and then processed into briquettes for use in industries.

2.8 Plantation residues

Wood stock is the basis of paper industry; it is also the basis of furniture industry. It is used in the form of poles as scaffolding in construction industry. These operations generate wastes because the small branches called as lops and tops are not used as prime feed stock in the paper or other industries. There are also tree fallings during storm and rain. These wastes are generally left around and may be taken away randomly for domestic applications or for burning. The lops and tops constitute about 30 % of the prime stock. In addition, biomass is grown specifically as energy forest. This is beginning to be practiced widely in the west as a part of mitigation of emissions related to climate change. When these plantations are grown, specific attention is given to the choice of the species, addition of nutrients and providing of water as

Table 2.8: National availability of crop residues for heat/power in India 2007-2008

Crop	Area	Prodn total	Residue Name	CRR (+) R:C	Residue	Surplus Residue	Power
	mha	*mmt*	-	ratio (w)	*mmt*	*mmt*	*MWe*
Paddy	41	90.00	Straw	1.5	135.0	35.0	4000
			Husk	0.2	21.0	10.0	1500
Wheat	22	60.00	Stalks	1.5	90.0	15.8	1400
			Pod	0.3	18.0	8.1	720
Cotton	8	5.70	Stalk	3.8+	30.0	16.4	2000
			Husk	1.1	6.3	4.3	450
Maize	6.25	11.00	Stalks	2.0	21.0	4.2	400
			Cobs	0.3	4.8	1.8	220
Groundnut	6.4	6.60	Stalk	2.0	13.6	2.1	200
			Shell	0.3	1.9	1.2	100
Soybean	7.25	7.25	Stalks	1.7	12.8	3.3	300
Coconut	1.8	6.00	Fronds	4.0+	7.2	3.6	350
			Shells	0.2	1.2	0.9	130
			Pith	0.53	3.2	1.5	140
Topioca	0.21	5.50	Stalks	0.83	5.5	3.2	380
Jowar	9.3	9.40	Stalks	1.7	16.1	2.2	190
			Cobs	0.5	4.7	2.2	200
			Husk	0.2	1.9	1.1	80
Arhar	3.5	2.70	Stalks	2.5	6.8	0.8	60
			Husk	0.3	0.4	0.2	10
Bajra	8.33	5.92	Stalks	2.0	11.8	1.9	160
			Cobs	0.33	1.9	0.9	90
			Husk	0.3	1.6	0.4	30
Mustard	6.27	6.27	Stalks	1.8	11.3	3.0	280
Ragi	1.4	2.0	Straw	1.3	2.6	0.2	10
Til	1.1	0.8	Stalks	2.25	1.8	0.6	30
Coffee	0.35	0.3	Prunings	1.4+	0.4	0.3	60
Arecanut	0.26	0.26	Fronds	3.0+	0.8	0.3	20
			Husk	0.8	0.2	-	-
Barley	0.7	1.3	Stalk	2.0	2.6	0.5	-
Potato	1.37	23.2	Stalk	0.8	18.5	3.0	200
Onion	0.55	6.6	Stalk	0.2	1.3	0.5	-
Banana	0.5	16.0	Stems	1.0	16.0	3.0	200
Mango	1.5	10.5	Stones	0.1	1.0	0.8	70
Other fruits	1.8	18.1	Wastes	0.2	3.6	1.0	80
Total	128.8	295.8			471.0	137.9	13570

CRR = crop-to-residue ratio; (+) tonnes per hectare in these four cases

Table 2.9: Productivities of different oil seeds (the production of oil from the seeds is about 30 to 40 %)

Crop species	Output oil $t/ha/year$
Palm	3.7 to 6
Coconut	2.2
Brazil nuts	2.0
Jatropha	1.6
Jojoba	1.5
Rapeseed	1.0
Groundnut	0.9
Sunflower	0.8
Pongemia	0.8
Soybean	0.4

appropriately needed for maximizing the growth. These have been practiced widely in Brazil over hundreds of thousand hectares. India has about 3.5 mha of plantation on Eucalyptus and other species (PC, 2010; IPMA, 2010; FAO, 2010). Use of Eucalyptus as plantation species, both by private and government agencies underwent severe controversy on its possible ill-effects on the environment. However, many studies showed that the ill-effects are exaggerated and the major outcome was to use mixed plantation as a principle since such an action allows the local conditions to allow better growth of those species that are better suited to the location. One of the important issues about growing such plantations is the economic return. In the case of private lands, there are owners who may not want to put in much care, yet wanting the land to be productive. The maximum output per year after typical four to five year maturation is about 5 dry t/ha. However, paper industries own their own plantations for generating the feed stock for their industry and have recorded as much as 20 dry t/ha. Many field experiments over large acreages (hundreds of thousand hectares) have shown that the output of solid stock is up to 25 dry t/ha. Also bamboo plantations all over the world have also demonstrated this class of output. In summary, it can be stated that while sugarcane productivity is 50 dry t/ha, many other agricultural crops like potato, banana and tree based solid biomass productivity can reach 25 dry t/ha.

2.9 Liquid biofuels and waste land utilization

In the last few years a new imperative has got imposed on oil importing developing countries. The increasing costs of crude argued by many to be linked to “peak oil” phenomenon (oil extraction all over the world has reached a peak; see for Hubbert’s theory, Wiki-Hubbert, 2010) have led to vigorous search for alternate sources of renewable oil. Oil from seed bearing crops edible or preferably non-edible (for avoiding competition between food and fuel) has been identified as the alternate. Jatropha curcus, Pongemia, Cashew, Sal and Mohua are one set of alternates. Palm and castor are other alternates that have been explored. Coconut oil and groundnut oil are avoided as they are important ingredients for human consumption. Palm oil is extensively produced in Malaysia with very high productivity and hence is considered an attractive alternate [Donoughm et al, 2009]. The relative productivities of these oils is presented in Table 2.9. One can notice the significant difference in the productivity of palm oil compared to other plants. Yield is also being improved through better-quality seeds developed via intensive breeding and selection research over the last 50 years. Although the national average yield is 3.7 t/ha/year,

Table 2.10: Culturable Waste land decomposition (table drawn from internet-posted data from NRSA, Hyderabad; the total land area is 328 mha)

Nature of land	Land area mha	Fraction %
Land with or without scrub	18.79	5.9
Under-utilized/degraded, notified forest land	12.65	4.0
Degraded pastures/grazing land	0.19	0.6
Shifting cultivation area	0.19	0.6
Gullied and/or ravinous land	0.19	0.6
Waterlogged and marshy land	0.10	0.3

high-yielding individual elite palms can regularly achieve over 10 t/ha/year.

Oil Palm requires a well distributed rainfall of 1500–2000 mm or more without long period of drought (no more than 3 months below 100 $mm/month$). The average relative humidity should preferably be over 75%. For maximum production, the plant requires a high light intensity with at least 1500 hours of sunshine per year. The optimum temperature ranges from 25 to 30°C. Oil palm can be grown on a wide range of soils. The most suitable soil would be one with a deep, well drained and well structured with unrestricted rooting medium of reasonably good water holding capacity. Whenever possible, flat or undulating land should be chosen. Steep land may be utilized and the oil palms are normally planted on terraces as a means of soil conservation measure to prevent soil erosion. Cost of establishment and production will also be increased. A pH of 4.0 – 6.0 is considered favourable.

The subject of growing Jatropha and Pongemia plantations has received sporadic attention from several sources with inadequate results. There are also debates about food vs fuel when it comes to growing these plantations on the current agricultural fields. Suggestions are made to grow them on waste lands. The extent of waste lands in India has been assessed in a major effort of National Remote Sensing Agency under a project of the Ministry of rural development of the Government of India. These maps and the data can be accessed on the internet. These data are presented in Table 2.10 and Figure 2.13. The waste land described under the thirteen classifications amounts to 55.3 mha, the culturable waste land that can be used to grow plantations is 32.11 mha. This land can be used to grow oil seed bearing trees of the desired kind with appropriate inputs. It has been argued that by culturing the land initially and using the right choice of species and inputs like water, and fertilizers the land can be made to yield high throughputs of oil seeds and other tree wastes. These can then form the basis of producing bio-oils to replace the fossil fuels (high speed diesel, in particular). While eucalyptus, causarina, acacia and more recently, bamboo (a grass) are the crops thought of as a part of energy plantation, miscanthus, switch grass and short rotation coppices like willow and poplar are considered suitable grasses and plants to grow for energy purposes. In the new environment when oil from land crops is intended to replace liquid fossil fuels, one needs to optimize the land output in relationship to the inputs required to derive the output. Classically, the land output would be between 15000 to 20000 Rs/ha, they would go to 35000 to 40000 Rs/ha when oil crops are grown. This change would tilt the balance in favor of oil crops in times to come, provided state encourages the plan to buy up the oil with suitable specifications. One feature of importance is that oil crop growing should be encouraged on waste lands not currently under the classification of agricultural land. This will ensure avoidance of the food vs.fuel debate that has come up severely after the efforts in the USA where corn was diverted from food to fuel.

With such thinking, it would be possible to achieve liquid fuel output of up to 30 $mmt/year$ along with solid residue output of 120 to 150 $mmt/year$.

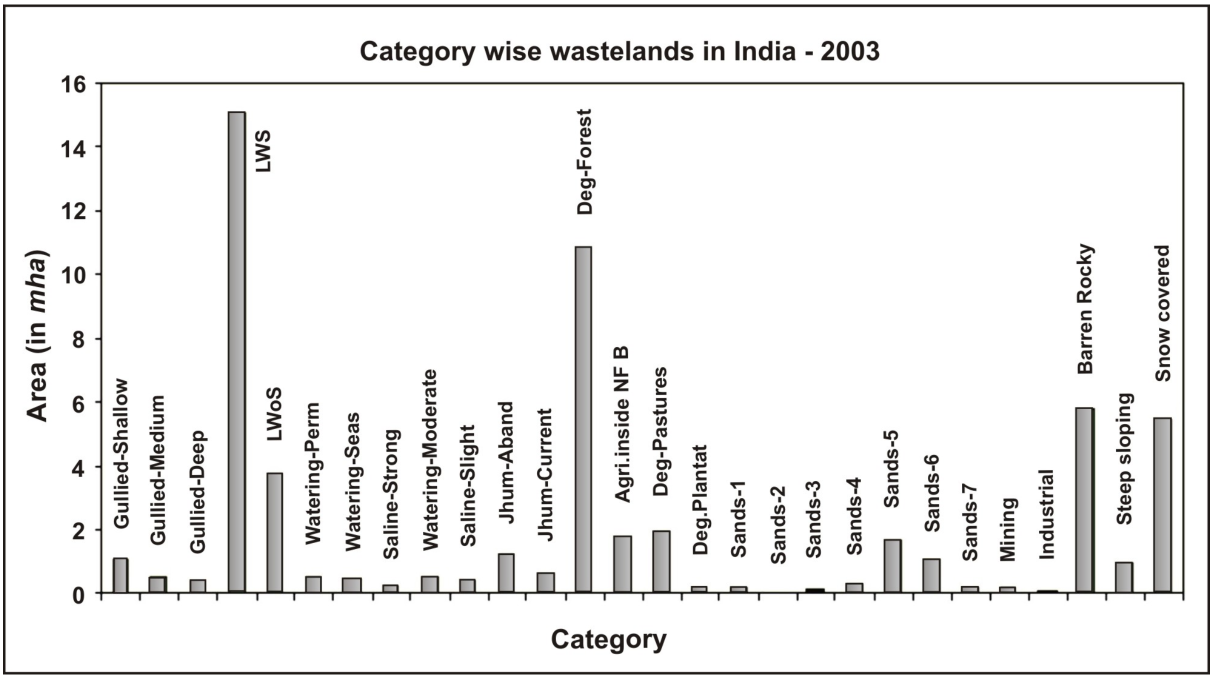

Figure 2.13: The distribution of waste lands in India (NRSA, 2005)

2.10 Urban solid wastes

Societies are becoming more and more urbanized because of greater job opportunities and better quality of living. This has been particularly so in India. The degree of urbanization has grown to 35 % and is likely to increase. There are many side problems associated with this urbanization - creation of slums in cities and lack of suitable work force to carry out farming activities in villages, a problem made more acute because of low land holding size, a subject brought out earlier. The migration has led a new class of poor - urban poor that do not have enough dwelling space leading to difficulties in adoption of cooking solutions that could have been adopted in the rural environment.

The rural environment produces little waste that needs serious consideration. They can easily be recycled as manure into the farms or used for producing composts in small quantities. Urban environment has created packaged foods increasing over a period of time. These will inevitably produce wastes that are a mix of plastic components and paper. A study conducted in the year 2000 under the ministry of non-conventional energy showed that out of 300 class I cities in India, 20 cities have generation rate in excess of 1000 TPD, and 80 cities generate 150 to 1000 TPD (Sharholy, 2008; see some aspects of statistics in Dhussa, 2007).

The balance 200 cities (68 %) individually generate less than 150 TPD. The magnitude of urban solid waste on a per-capita basis has increased from about 0.3 to 0.8 $kg/person/day$, with metros like New Delhi, Mumbai, Kolkata, Chennai, Bangalore, and Hyderabad at higher end of the scale and other cities and towns with population of 200,000 or less towards the lower end of the scale. Amongst the plastic components are polythene in the form of bags from the very thin ones to slightly thicker ones (20 microns is the smallest thickness), polyvinyl chloride in the form of footwear and tires that may contain poly-butadiene and natural rubber with chlorine and sulfur as other elements. The magnitude of plastics in the urban solid waste is about 6 % or less. Many plastic items are taken away by rag-pickers for recycling purposes. It is the

Table 2.11: Typical composition of wastes, %

Physical features	Veg. market	Commerce zone	Industry zone	Domestic zone	Dump site	Truck sample
Paper	3	80	70	10	6	3
Newspaper	2	10	2	5	4	2
Plastic waste	3	5.5	20	2	23	12
Coconut shells	5	4.5	-	0.2	12	8
Veg+non-veg waste	72	-	-	64	24	45
Cloth waste	5	-	2	6.8	21	19
Rubber waste	1	-	2	12	1	1
Glass	-	-	-	-	-	-
Metals	2	-	4	-	2	-
Debris	5	-	-	-	5	-
Grass/dry leaves	2	-	-	-	2	10

not-useful items like fine plastic bags that cannot be separated and tires that appear in bad shape are allowed to remain in the waste. There are also metal components and glass bottles and other broken glass material that will find their way into the waste. Metal components are treasured items and will be taken away by rag-pickers; so also glass-ware. However, tiny metal objects like nails and broken glass pieces will remain in the waste.

One of the other serious problems in urban solid wastes in India is the presence of demolition debris from civil structures. There is growing understanding that these should be separated at the point of origin, but implementation is slow. Further, there are festival seasons when a large amount of biomaterial like banana stems, leaves and peals will appear over a short time - about a month in different cities and different seasons. Added to this, there are seasonal variations of moisture in the biomass. During period of winter and hard summer, the average moisture content of the waste may drop to 10 %, but go up to 60 % during rainy seasons that will occupy about 40 days in a four month period. The other material in the waste that is about 50 % will be biodegradable material.

Since the source separation methods have not penetrated the Indian urban waste management scene, it is advisable for all waste to energy projects to consider waste processing scheme that has the separation techniques related to magnetic metals, non-magnetic metals, glass and building related debris. Further, the magnitude of energy-rich waste must be estimated and plant design should be for a minimum to avoid problems associated with inadequate throughput after the plant has been built and has operated for a certain period of time. Several studies have been conducted to assess the solid waste and their composition. The actual composition is a strong function of source as clearly shown in Tables 2.11 and 2.12. Vegetable market and residences peak in vegetable wastes and the commercial and industrial zones peak in paper and plastic waste. The dump sites however have a mix with vegetable wastes still having a much larger share than the others. While the data in these tables are from some dump sites of Mumbai in 2004 [NMMC, 2004] and the situation on wastes is always dynamic, the broad features remain valid for reasonable period of time. The magnitude of heavy metals is not small in larger cities. The actual distribution depends strongly on the industrial activity. With insufficient regard for the seriousness of disposal of these wastes, the wastes appear at the dumping yards rather randomly making it difficult to design quality measures of handling them. But, thermal treatment techniques offer a better choice of containment than low temperature biochemical techniques.

It appears from Table 2.13 that tannery occupies the largest amount of waste waters that need to be handled. Dairy industry occupies the second largest in terms of magnitude. Distillery

Table 2.12: Composition of heavy metals, n.d - not determined, Arsenic, Cadmium n.d

Heavy metal	Veg. market	Commerce zone	Industry zone	Residence zone	Dump site - 1	Dump site - 2
Lead, mg/kg	0.52	0.65	0.41	0.52	3.1	3.0
Mercury, mg/lit	0.2	n.d	n.d	n.d	7.2	28
Nickel, mg/lit	n.d	15.2	18	4	n.d	n.d
Iron, g/lit	0.15	2.42	2.21	1.18	0.11	0.1
Copper, mg/lit	8.2	0.32	0.39	0.18	14.0	14.1
Chromium, mg/lit	0.21	n.d	0.86	n.d	0.52	0.11
Zinc, mg/lit	6.8	0.01	n.d	n.d	4.91	n.d

Table 2.13: Liquid industrial wastes in India

Waste	Magnitude
Distillery effluents	9000 m^3/day
Dairy industry	70000 m^3/day
Paper and pulp industry	1600 m^3/day
Tannery	0.6 million m^3/day
Food processing	5 $mmt/year$

effluent treatment plants have been implemented far more intensely. Tannery effluents are perhaps the most complex of the wastes. Dairy effluents are the most dilute of the effluents.

Discharge of all these effluents into existing streams requires that they be treated to reduce what are known as Bacterial Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) to sufficiently low levels. Both the BOD and COD tests are a measure of the relative oxygen-depletion effect of a waste contaminant. BOD is the amount of oxygen, expressed in $mg/liter$ or parts per million (ppm), that bacteria take from the water when they oxidize organic matter whereas COD measures the chemical oxygen demanded to oxidize the pollutants, again expressed in terms of $mg/liter$.

If waste waters are discharged in unduly large amounts into natural streams that may contain species like fish, these fish do not find enough dissolved oxygen for their existence and therefore will die. There will also be a change in the color of the water. Usually, this is how habitats living downstream of a large factory that generates such pollutants but discharges them before full treatment will begin to notice. One standard measure is a 5-day BOD measure at 20°C that presents the amount of oxygen consumed by biochemical oxidation of waste contaminants in a 5-day period. Historically, these specifications were brought out by British Royal commission because British rivers do not have a flow time to the open sea greater than 5 days and average long-term summer temperatures do not exceed 18.3°C. The temperature has been rounded upward to 20°C, but the 5-day time period has become the universal standard! This is also considered adequate compared to what is known as ultimate BOD as it takes much longer to obtain. Similarly, there are different COD measures of which a 4-hour COD is most commonly accepted. A COD test measures all organic carbon with the exception of certain aromatics (benzene, toluene, phenol, etc.) which are not completely oxidized in the reaction. COD is a chemically chelated/thermal oxidation reaction, and therefore, other reduced substances such as sulfides, sulfites, and ferrous iron will also be oxidized and reported as COD. There are also nuances in conducting COD tests and deriving conclusions because NH_3 (ammonia) will not be oxidized in a standard COD test since potassium dichromate which is used as a reagent does not oxidize NH_3.

There is another measure called total organic carbon (TOC). It measures all organic carbon as CO_2. TOC is a good parameter to measure and actually a more accurate indication of some of the pollutants that cause the most problems than a BOD test. TOC does not differentiate between that part of organic carbon, which can be assimilated and the chemically oxidizable carbon.

The process of anaerobic digestion (biomethanation) reduces the BOD and COD of an effluent significantly. However, this reduction is usually inadequate for discharge of the effluents into natural bodies. A further treatment by aerobic means is usually required to ensure compliance with regulations on the quality of discharge waters.

In so far as thermo-chemical means of conversion, projects on waste to energy have had many problems, one of them being the problems of emission of dioxins from waste-to-energy plants. While these issues have been addressed in many plants built overseas, several men-in-authority still retain old notions and stone-wall projects related to waste-to-energy (some of the technical points will be addressed in the later chapters). Building waste-to-energy plants that can take care of seasonal variations in the magnitude and quality of wastes and run them in an economically meaningful way is a challenge that has to be taken up in India.

2.11 Summary

This chapter is concerned with (a) aspects associated with biomass production from photosynthesis, (b) the amount of bioresidues available in India for energy purposes.

Many aspects of photosynthesis in plants have been understood in sufficient detail. C4 plants like sugarcane enjoy a higher efficiency due to reduced respiration. The photosynthetic efficiency of many C3 plants, like rice, maize, potato and banana is not far behind. In India productivities of many staple crops are 50 to 70 % of those achieved in other countries. Thus there is much room for increasing the productivity. In so far as tree crops are concerned, the situation is about the same.

Agricultural crops are grown with photosynthetic efficiency of 0.1 to 8 %. Sugarcane, potato and banana show high productivity. The maximum biomass produced is about 50 dry $t/ha/year$. Plantation wood production can reach about 25 dry $t/ha/year$. Efforts to grow bamboo at 50 dry $t/ha/year$ are being made. These make it possible to enhance the role of renewable energy in the energy mix of the country.

There is considerable culturable waste land in the country that can be used for growing fuel crops instead of food crops without the fear of creating food vs fuel controversy in the country. This approach has the promise of replacing fossil fuel import by a significant amount.

Urban solid wastes also contain biomass and plastics with varying shapes sizes and moisture content along with non-combustibles. Handling urban wastes needs additional upstream treatment of the incoming wastes to separate the combustibles and process them before further application. Some of these will be addressed in subsequent chapters.

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3 Routes for conversion of biowastes

3.1 Introduction

It has been brought out that biomass can be the source of food, fodder, fiber and fuel. The fuel can be liquid or solid. Liquid fuels promise the possibility of meeting transportation requirements and some routes perhaps most economically since nature has already loaded the liquid fuel into the seeds of select trees/plants. There are food industry related liquid wastes that cannot be discharged unless the offensive fragments are brought below a specified level. Solid biomass is used in so many ways that wastes get generated significantly.

The principal classification points for the use of wastes for energy conversion turn out to be moisture content and the extent of lignin in the substrate. Those that have high moisture - beyond 70 % and with little lignin (say, < 10 %) qualify for bacterial conversion process - the process of biomethanation that leads to a gas composed largely of methane (CH_4) and an inert, carbon dioxide (CO_2). As different from this, those that are reasonably dry - moisture < 30 % will ideally qualify for thermo-chemical conversion. Thermo-chemical conversion processes come in great variety - those that lead to producer gas and synthesis gas that can further be processed to get liquid hydrocarbons or alcohol. Much attention has been paid to this area because *95 % of the waste biomass use* is via thermo-chemical conversion route [Klass, 1992 (p. 192)].

There are several wastes that fall in between the extremes. Take the case of bagasse, a waste of sugar industry. It comes out of a sugar mill at about 50 % moisture. It is lignaceous. It is largely used in combustion route without even further reduction in moisture. A small part is used in small jaggery making units distributed widely (also called Khandsari sugar industry) and in these cases some amount of open air solar drying gets done. Sugar industry has effluents related to molasses. These have small solids fraction (< 10 %) and qualify for biomethanation; this is in fact the standard industrial practice.

Urban sewage when transported underground over distances before consideration of treatment will be at 2 to 4 % solid concentration. Even for biomethanation, the solid concentration is to be increased to about 10 to 12 % as is practiced. There are requirements in some situations for zero-discharge of effluents. In these cases, one will need to use reverse osmosis coupled with biological treatment processes or thermal systems that evaporate most of the moisture, producing solids that can be burnt in furnaces with devices for limiting the gaseous emissions as well.

Most biomass at the time of harvest will be at 50 to 60 % moisture. Many agricultural residues are light with thin walls so that spreading the material on ground in the open will reduce the moisture to 20 % or less in a few days. Wood stock with sufficient girth takes longer to dry in the open air. However, wet stock is easier to split and cut. Thus, sizing operations can be done in the green condition and then the material allowed to remain in the open for the moisture to reduce to about 30 %. Reduction of moisture below this level requires drying operation

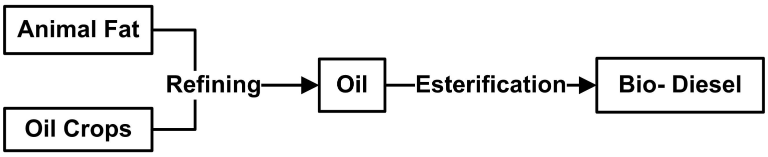

Figure 3.1: Routes for energy conversion

to be conducted. Many times it is economical to reduce the moisture from 50 % to 10 % which is the equilibrium moisture under shade in tropical countries. Reducing the moisture to *as low a value as possible is an important imperative* for most thermo-chemical conversion processes to derive high efficiency of conversion to useful high grade heat or electricity (a subject that will be addressed subsequently).

Figures 3.1 and 3.2 illustrate the various routes of conversion. We will discuss each of these routes below.

3.2 Routes to bio-diesel

Two sources for bio-diesel are: waste oils and fats used in domestic or food industry environments as well seeds from oil-seed bearing trees. There are several trees already discussed in chapter 2 (see Table 2.9). The seeds are dried and subject to screw extraction to obtain oils. Residual oil extraction is performed by a solvent process. These are called Straight Vegetable oils (SVO) and can be used with minimal filtering to remove extraneous solids directly in stationary reciprocating engines. These oils as well as the waste oils can be mixed if needed and then subject to trans-esterification process which consists of reaction of these oils with ethyl or methyl alcohol and separation of the ethyl or methyl ester from glycerine. These esters form the fuel for use in reciprocating engines replacing the diesel or heavy fuel oil. Knothe et al (2005) provide a good summary of the history of plant oils and biodiesel from many perspectives. These are discussed in more detail in chapter 10.

3.3 Other routes

The low temperature processes are those of biomethanation and fermentation. These lead to gaseous fuel called the biogas or liquid fuels like ethyl alcohol. High temperature processes are several. Combustion releases heat directly and can be used to raise steam at high pressure for use in steam-turbines for electricity generation. Pyrolysis leads to crude liquid fuel that can be used for combustion directly or can be used as a feedstock for refinement into hydrocarbons. Gasification with air leads to a gaseous fuel that can be used for high grade heat or electricity applications. Gasification with oxygen-steam combination leads to a gas called syngas that becomes the feed gas stream for conversion to liquid hydrocarbons. Many of these ideas and technology aspects are discussed in literature [Agbontalor, 2007; Klass, 1998; Sims and Sayigh, 2004, Rezaiyan, J and Cheremisinoff, N. P. (2005) Gruddmann et al, 2007]. These are described in some detail.

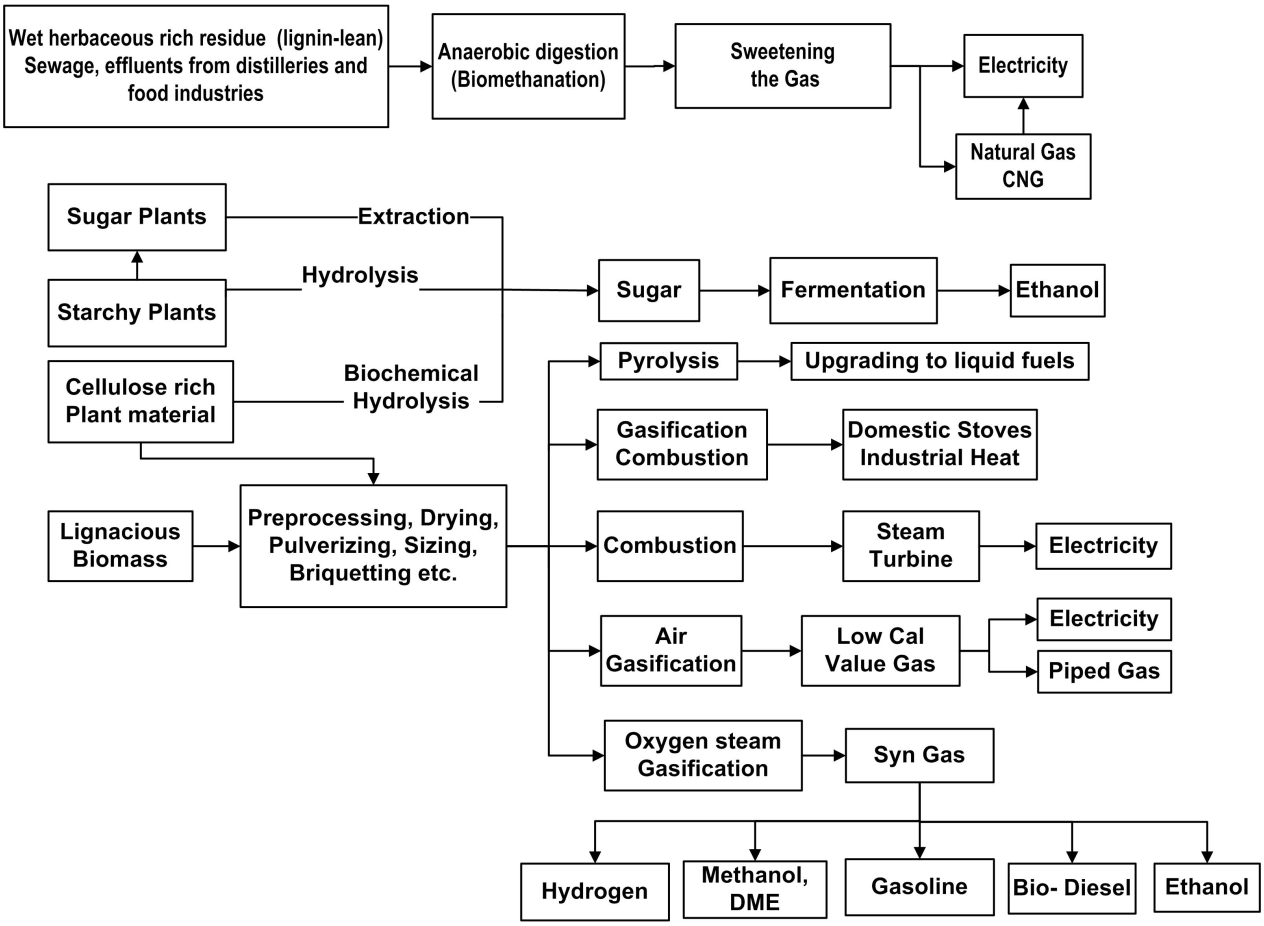

Figure 3.2: Routes for energy conversion

3.4 Biomethanation

The biochemical route works with bacteria and occurs at temperatures not exceeding 60°C, more usually at 37 - 40°C or 50 to 55°C each of these being a separate class of bacteria, mesophyllic and thermophyllic respectively. The reactions stop at temperatures below about 10°C. In either of these processes, there are essentially four steps.

The first step involves the fermentative bacteria including both anaerobic and facultative (aerobic/anaerobic) microorganisms. carbohydrates, proteins, lipids and some very complex organic compounds are hydrolyzed and fermented into monomers, fatty acids, alcohols, carbon dioxide, hydrogen, ammonia, and sulfides.

In the second step, acedogenic bacteria convert the hydrolyzed monomers to acids.

In the third step, the acids are converted into acetic acid, propyonic acid, butyric acid and some amounts of carbon dioxide and hydrogen.

The fourth step uses two distinct types of methanogenic bacteria. One type reduces carbon dioxide to methane, and another, decarboxylates acetate to methane and carbon dioxide.

The objective of the biogas process is to degrade all appropriate organic matter to methane. Therefore, it is important to optimize biochemical conditions for all reactions leading to the formation of methanogenic precursors and, most importantly, for those reactions responsible for the formation of methane itself. At the same time, production of carbon dioxide, nitrogen, and other gases which dilute the energy content of the gas should be minimized to the extent possible.

Biogas plants based on bovine dung at domestic levels have been built in India and China in millions. Larger size plants have been built for other residues like distillery effluents or dairy plants with the gas going in for steam raising or power generation or both. Sometimes, starch mill effluents are combined with dairy wastes. Typical dry gas composition (volumetric) from biogas plants will be CH_4 of 50 to 75 %, CO_2 of 25 to 50 %, and some amount of H_2S. In the case of cow dung based plants, the fraction of H_2S is indeed small, a few hundred ppm. For other meat-related animals, the wastes contain up to 0.2% H_2S since the food served to them contains sulphur. Distillery effluent based biogas plants are the ones that produce significant amount of H_2S, up to 5%; 3 to 4% is common. In order to enable the gas to be used for power generation in reciprocating gas engines, it is essential that H_2S must be eliminated from the gas or brought to a few hundred ppm level to prevent corrosion of components (H_2S is very corrosive with regard to copper and other components). The gas that has H_2S is called sour gas and the process of removal if often christened "sweetening" the gas (as noted in the top part of Fig. 3.2). Typical residence times required for conversion of the solids to gas depend on the substrate and the temperature at which the system is operated. Typically, for sugars 12 hours is adequate, for starch about 24 hours and for cellulose about 48 hours. Accounting for systemic deficiencies in operation, one week is usually adequate for complete digestion at 37°C or even less at 55°C. In actuality, systems operating at ambient temperature for a variety of substrates are designed for residence times of about 30 days and considerable material (up to 50%) is left behind even after this period. A question of significance is that even if the conversion in a certain period (say a week) is not very high, would it be appropriate to design the system for this limited residence time to gain on the size of the system and consequent benefits of first cost of installation; the residual material can be subject to thermal conversion if so needed. There is much scope for designing systems, particularly small size systems that are more compact and efficient. Such an opportunity should actually be converted into a commercially meaningful proposition for the new technology to spread.

3.5 Fermentation

Fermentation is the anaerobic enzymatic conversion of organic compounds, especially carbohydrates, to simpler compounds, especially to ethyl alcohol, an energy source. Though this is the normal route for fermentation, it does not have to be carried out in an anaerobic environment always. Even in the presence of abundant oxygen, yeast cells prefer fermentation to oxidative phosphorylation, as long as sugars are readily available for consumption. Sugars are the most common substrate of fermentation with ethanol being an important product. Carbon dioxide is another gaseous product of fermentation.

When reactions begin with yeast, the initial concentration of glucose ($C_6H_{12}O_6$) will be very high, so through diffusion, glucose enters the yeast (in fact, this process ends only when all glucose is exhausted). As reaction proceeds, glucose molecule is broken down in a 10-step process called glycolysis. The product of glycolysis is two three-carbon sugars, called pyruvates, and some ATP (adenosine triphosphate, brought up earlier in photosynthesis process), which supplies energy to the yeast and allows it to multiply. The two pyruvates are then converted by the yeast into carbon dioxide (CO_2) and ethanol or ethyl alcohol (CH_3CH_2OH). The overall reaction is:

$$C_6H_{12}O_6 + \text{Yeast} \rightarrow 2CH_3CH_2OH + 2CO_2$$

3.6 Pyrolysis

Pyrolysis is a process in which the solid fuel will be converted at high temperatures to vapor and gases in the absence of any oxidant. The output can be condensed to ambient temperature to lead to water and some complex oxygenated hydrocarbons in the form of liquids and permanent gases like CO, H_2, and CO_2 and CH_4. There is also residual solid in the form of char. The fraction of solids, liquids and gases will depend on the rate of temperature rise and the actual temperature to which it is raised. Typically, volatiles begin to evolve at about 300 to 500°C depending on the actual biomass considered. At a low end, drums built to carry petroleum tar and other crude oils is often used to produce char by burning away the volatiles leading to 20 to 30 % char. Methods of controlled heating by combining the heating rate with the temperature to which the biomass is raised leads to chars of different fractions and quality. Slower heating rates and achieving high temperatures (pyrolysis has been considered even up to 1000°C) leads to much larger fraction of gases. Slow pyrolysis is a standard process used to produce charcoal. Faster heating rates tend to produce more liquids, because there is not adequate time for the liquids to react and form simpler compounds. High heating rates (of 1000°C/s) with residence times of 0.7 - 1 s in a process called fast pyrolysis are used to generate liquids. These liquids can be directly used for combustion applications or they can become a feedstock for conversion to straight hydrocarbons in another process [Mohan et al, 2006]. These are discussed in greater detail in Chapter 9.

3.7 Combustion

Combustion is a process by which biomass combined with air or oxygen is reacted after suitable ignition to lead to a high temperature conversion process where carbon is oxidized to carbon dioxide and hydrogen to water vapor. Of course, at high temperature there may be other products of decomposition too in smaller amounts. Combustion will occur in furnaces at ambient pressure or high pressure. Since a large part of biomass is ultimately thermo-chemically handled, this will be a subject of detailed discussion (the next chapter).

3.8 Gasification

Gasification is often treated as sub-stoichiometric combustion process. This is only partly correct, because during combustion, inadequate supply of air can also lead to sub-stoichiometric combustion. But this is not gasification, because the results are due to poor mixing of air and fuel with local regions with highly imbalanced air-to-fuel ratio. *Gasification is a combination of oxidative pyrolysis and hot-char caused reduction reactions* achieving a gas composition as close to equilibrium (under excess char condition) as is possible. The oxidative pyrolysis is also a reaction that occurs under sub-stoichiometric conditions and therefore sub-stoichiometric combustion process. Achieving composition close to equilibrium in the presence of excess char at reasonably high temperatures is a feature that ensures good cracking of tar components.

Gasification as a process has been known for a long time (about 200 years) and the World War II saw extensive development and use of a closed top design for wood chips. Most concentration in Europe and in the Americas (both north and south) has been with regard to use of wood chips because of their extensive availability. The research and development that was done on gasification was mostly aimed at solving specific problems faced during the war (shortage of fossil fuels in the European war theatre). Subsequently, it became a subject of development by research enthusiasts with little additional hard inputs to research. This is the reason why the subject remains active on research agenda of the European Union as well the USA. Most concentration of research and development in Europe and the USA has been at large throughputs and power levels ($\sim$ 10 to 100 MWe). Substantial research and development inputs on small gasification systems (25 to 1000 kWe) have been provided by work in India and it is considered one of the leading nations in this area. A principal requirement of the gasification system is to reduce the tar content to the minimum most with little load on the cooling and cleaning system for the removal of tar so that system operation is smooth.

A typical gasifier has the features of biomass drying, volatilization and oxidative pyrolysis, and reduction by char. Typical maximum temperatures experienced inside the system go up to 1400°C. Typical residence times for the biomass (reactor loading/rate of throughput) are on the order of 3 to 5 s and the solid residence time is about an hour.

Air as the oxidant for gasification is used to get a gas with a dry volumetric composition of CO and H_2 about 20 % each, CH_4 about 1 %, CO_2 about 12 % and the remaining N_2. This gas is ideal as transportable clean gas for high grade heat or electrical generation. Oxygen can also be used as an oxidant most usually with steam or with wet biomass. The composition of the gas will be dependent on the mode of gasification and will generally generate 25 to 30 % CO, 30 to 40 % H_2, and the rest CO_2. This gas is better used for producing chemicals. Liquid hydrocarbons are intended final products when these are processed at high temperature and pressure with Fischer-Tropsch synthesis. This is currently a very active field of development in many advanced countries. The process requires H_2 and CO in 2: 1 molar ratio. This is not easy to obtain and for gaseous composition different from this, one needs to process the gas further. The process of synthesis gas to liquid hydrocarbons is complex with many parameters to be optimized including the choice of high temperature catalysts. It is generally understood that the process is economical only when handled at large throughputs. In India, of course such a demand is counterproductive because of biomass availability issues.

One of the adaptations of the gasification process has been to generate a design for a cook stove that would lead to high utilization efficiencies with minimal emissions. These concepts will be discussed in detail as they constitute the current day research and development in India and elsewhere.

3.9 Gasification vs. Biomethanation

It is perhaps useful to compare the process performance of biomethanation and gasification systems. Biomethanation can handle non-lignaceous biomass with greater facility for handling sugars and starches; Cellulose is also handled. Gasification process is not sensitive to the structural content of biomass. Biomethanation is friendly with water. While possibilities exist to limit the water fraction to 70%, the most conventional value is 90%. More dilute than this will increase the volumes handled and therefore the costs. But gasification is best handled with minimum water, sundry condition being an acceptable state. The residence time of biomethanation process is about a week and that of gasification system about a few seconds based on the gas or an hour based on the solids. This residence time ratio between biomethanation and gasification is about 200. This means that for the same throughput, the reactor size for biomethanation is about two-hundred times larger. This feature is moderated by the need for other elements of the gasification system for cooling and cleaning not required in the case of biomethanation as it is a low temperature operation. Yet the ratio is about 100. Gasification process is a high temperature operation with oxidation and reduction occurring in the same area at different times. This calls for the use of high temperature materials including ceramics. Biomethanation produces a gas that has hydrogen sulfide (H_2S) from a few hundred ppm to as high as 5 %. What is allowed into an engine must have H_2S no more than 0.1 %, even lower being better. This calls for an additional process step to remove the hydrogen sulfide.

3.10 Summary

This chapter is concerned with the routes of conversion of biomass. It is recognized that wastes of biomass appear in a number of forms - those that have a large amount of water fraction in them and those that have relatively low moisture content. Those that have large moisture (active biomass content of 5 to 15 %) are better handled by low temperature processes mostly using microbial conversion routes. Those that have relatively small moisture (30 to 50 %) can be dried economically and converted to energy or fuels through thermochemical conversion routes. A large part of the biomass in the world is thermally converted to energy, fuels and chemicals.

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4 Principles of Combustion

4.1 Introduction

Combustion is a phenomenon that releases the energy in the bonds of the molecules - one called fuel and another called oxidizer into sensible heat. The combustion process occurs largely in the gas phase and in a few cases on the interface between a solid and a gas, like in the case of the oxidation of char. In either case, gaseous molecules interact in a complex way. Generally, the fuel molecules are so complex (and even a stable diatomic molecule like oxygen is chemically not simple) that reactions take place via many pathways each step being a simple break-up or an addition. This implies that reactions occur by a break-up of large molecules into atoms or charged molecules by losing or acquiring an electron. We can define fuel and oxidizer in this backdrop as follows. Fuel molecules are those that can donate electrons from their structure and oxidizer molecules are those that accept electrons. Thus fuels are electron donors and oxidizers are electron acceptors. Depending on the ease of donating electrons and hunger for electrons, one can classify a given species in a given reaction as a fuel or an oxidizer. In most aspects of our concern fuels are a biomass species, an alcohol, bio-diesel, gasoline or kerosene as these are all made up of carbon, hydrogen largely and in some cases a small amount of oxygen; oxidizer is usually oxygen or air which is diluted oxygen (with 79 % nitrogen by volume). In an unusual situation of no concern to us here, in a reaction of oxygen with fluorine, oxygen acts like a fuel because fluorine is a more powerful oxidizer (in compounds like F_2O_3, F is the oxidizer and O is the fuel).

4.2 Properties influencing combustion (thermochemical conversion)

It has been brought out that biomass appears in a wide range of physical conditions - moisture, shape, size, density and ash content. Each of these has a significant influence on the combustion process. Table 4.1 shows these properties for a variety of biomass found in India. The degree of variation in the properties seen in table 4.1 is enormous. The moisture of most fuels will be around 50% at the time of harvest. Usually many agro-residues are left in the field for some time and the residues dry up except when faced with rain. Thin-leaved biomass like straws will dry up fast (a typical one-to-three day sun-drying brings down the moisture by 20 to 25 %). Moisture removal is an essential part of thermo-chemical conversion processes except in select steam based conversion processes meant for syngas. Drying system is usually integrated into advanced thermochemical conversion processes.

Density is an important parameter controlling the combustion process. Except for coconut shells, most other thin walled biomass like Ipomia, Lantana camara and the straws have a low density with odd shapes. Transportation of these materials is a difficult economic proposition since their volumetric loading is very small. The only way of overcoming this problem is do some densification like baling, briquetting (or pelleting). Baling raises the density only moderately.

Table 4.1: Physical properties of various biomass (fresh biomass has 50 to 55 % moisture, ρ_f^* = dry density, ^{d} = dry biomass basis, w = wet at 50 % moisture, ^{b} = with bark, ^{s} = pick-up from soil, th = thickness, L = long, W = Wide)

Species	Native shape	Native size	ρ_f^* kg/m^3	Ash^d %
Ipomia (weed)	Hollow tube	3 mm wall	$\sim$ 200	4 - 5
Lantana Camara	Hollow tube	2 mm wall	$\sim$ 250	3 - 4
Prosopis Juliflora	Odd branches	20 - 50 mm	$\sim$ 500	1 - 4^b
Sawdust	Thin flakes	1 - 3 mm	300 - 500	1 - 10^s
Eucalyptus branches	Odd cylindrical	$\sim$ 25 mm dia, 2 m L	400 - 600	1
Bagasse (sugarcane)	fibers	1 - 2 mm dia , 50 mm L	$\sim$ 400 (w)	2
Sugarcane leaves	Like leaf	1 mm by 50 mm by 1 m	$\sim$ 50	5
Groundnut shells	Flakes	1 mm th - 10 mm wide	$\sim$ 250	3
Cotton stock	Odd branches	2 - 15 mm dia, 100 mm L	$\sim$ 400	3
Corncobs	Cylindrical	50 mm dia, 150 mm L	$\sim$ 350	2
Coconut shells	Thin pieces	5 mm th, $\sim$ 80 mm W	$\sim$1100	1
Coconut fronds	Long and thick	50 mm th, 1 - 3 m L	$\sim$ 300	3 - 5
Palm fronds	Long and thick	50 mm th, 1 - 2 m L	$\sim$ 400	3 - 5
Rice husk	Boat-like	1 mm th - 10 mm L	100 - 150	16 - 20
Rice straw	Long thin tube	1 mm th, 1 - 2 m L	$\sim$ 50	16 - 20
Wheat straw	Long thin tube	1 mm th, 1 - 2 m L	$\sim$ 50	10 - 12
Urban solid waste	Random	up to 200 mm	$\sim$ 200	10 - 30

It is only briquetting (or pelleting) that raises the density to 700 to 1200 kg/m^3. Such a transformation of biomass calls for drying and pulverizing as auxiliary processes. In many industries and at homes, loose as-received biomass is used directly. What is important to recognize is that such light biomass like straws and husks will burn up in the flaming mode very fast. Next in this group will be weeds like Lantana camara and Ipomia. Those that are fine but of medium density ($\sim$ 500 kg/m^3) may get packed to an extent that diffusion of air cannot occur. This is particularly true of sawdust. Bagasse is usually used even at 50 % moisture as combustion fuel to boilers in sugar industry. The fact that even moderate drying can provide significant benefits in terms of efficient use of the fuel that will ultimately translate into economic benefits has not penetrated the sugar industry. Smaller units get the benefit of using dried bagasse because they can be sun-dried except when occasional rains can upset this situation since such units do not have arrangements for covered storage. Sugarcane leaves (what is classically termed tops and leaves) are thin walled leaves and get sun-dried easily. Coconut shells are very dense, dry and have little ash. They are a prized feed-stock for activated carbon production. Because they are dense, they burn very slowly in comparison to light biomass like Ipomia, Lanata camara or cotton stock. This difference in the dependence of the burn rate (or time of combustion, more precisely) on the density of fuels is a fundamental property discussed in section 4.12.

Ash is a crucial feature of biomass. Wood, coconut shell, corncobs and a few other agricultural residues have little ash (< 1%). Some agro-residues like groundnut shell and coffee husk have moderate ash content 3 - 10 %; wood bark has an ash content of 4 - 5 %. It is only rice straw and rice husk that have high ash content. Rice straws (and other straws) are a important fodder base for livestock in India. Hence rice husk becomes the fuel of choice in most rice growing areas. While it is really an industrial waste, it is traded in rural areas as domestic fuel under conditions of non-availability of other fuels like firewood. Its use for combustion occurs at poor efficiencies with char and ash disposed in the most casual manner.

The role of the specific inorganic oxides in ash causing deposits on various components of high pressure boilers with superheat has been examined thoroughly in the USA as a consequence

Figure 4.1: Pictures of corncobs, broken coconut shells and sized pieces of wood

of a series of problems of use of agricultural residues in boilers in the eighties, particularly in the state of California (see Miles et al., 1996). More discussion on this is presented in section 4.13. Figure 4.1 shows pictures of corncobs, coconut shell and wood pieces. Amongst these, corncobs needs only drying, coconut shells may need to be broken to pieces for better throughput and wood may need to be sized for small size applications. Figure 4.2 shows a composite photograph of several agro-residues that can be briquetted for (a) economic transportation and (b) better combustion process management (more particularly for gasification process management). In the briquetting process, removal of external inorganic material is an essential element. Briquetted biomass even with reasonable ash content behaves in the combustion system in a manner much better than the way the original material would behave.

4.3 Ultimate analyses of biomass

All biomass is significantly “fuel” rich and so is called fuel. The fuel components are carbon, C and hydrogen, H elements. The fuel richness is moderated by oxygen in it. In chapter 2 (see Table 2.3) the essential structural components of biomass were set out as cellulose, hemicellulose, lignin and some extractives/crude proteins and ash. The molecular formulae of cellulose, hemicellulose, lignin and crude protein have been presented in Table 2.4. The actual fractions of C, H, N and O present in the biomass are expressed by the term *ultimate analysis*. Tables 4.5 and 4.3 show the data of the structural components, namely, cellulose, hemi-cellulose, lignin and (crude protein + extractives), the C, H, O and N analysis consistent with these fractions obtained from the chemical composition described earlier and the indices h, o and n in the average chemical composition $CH_hO_o\ N_n$. Both the structural and elemental composition are determined experimentally using standard methods. Table 4.5 shows the stoichiometric ratio in the last column. This will be discussed in section 4.4 It is possible to go from the structural analysis to elemental analysis and then to the chemical composition. It is instructive to see how this is done. Take the case of cellulose. In the formula, $CH_hO_oN_n$, The mass fraction of C, Y_C is $12/(12 + h + 16 \times o + 14 \times n)$ = $12/D$, where D denotes the denominator. Similarly we can write the mass fraction of H, Y_H as h/D, of O, Y_O as $16 \times o/D$ and of N, Y_N as $14 \times n/D$. Thus $Y_C \times D$ = 12, $Y_H \times D$ = h, $Y_O \times D$ = $16 \times o$, $Y_N \times D$ = $14 \times n$.

From these, we can get

$h = 12 \times Y_H/Y_C$, $o = (12/16) \times (Y_O/Y_C)$, and $n = (14/16) \times (Y_N/Y_C)$ Cellulose has 44.44 % C, 6.19 % H and 49.37 % O as can be noted from Table 4.5. This means Y_C = 0.4444, Y_H = 0.0619,

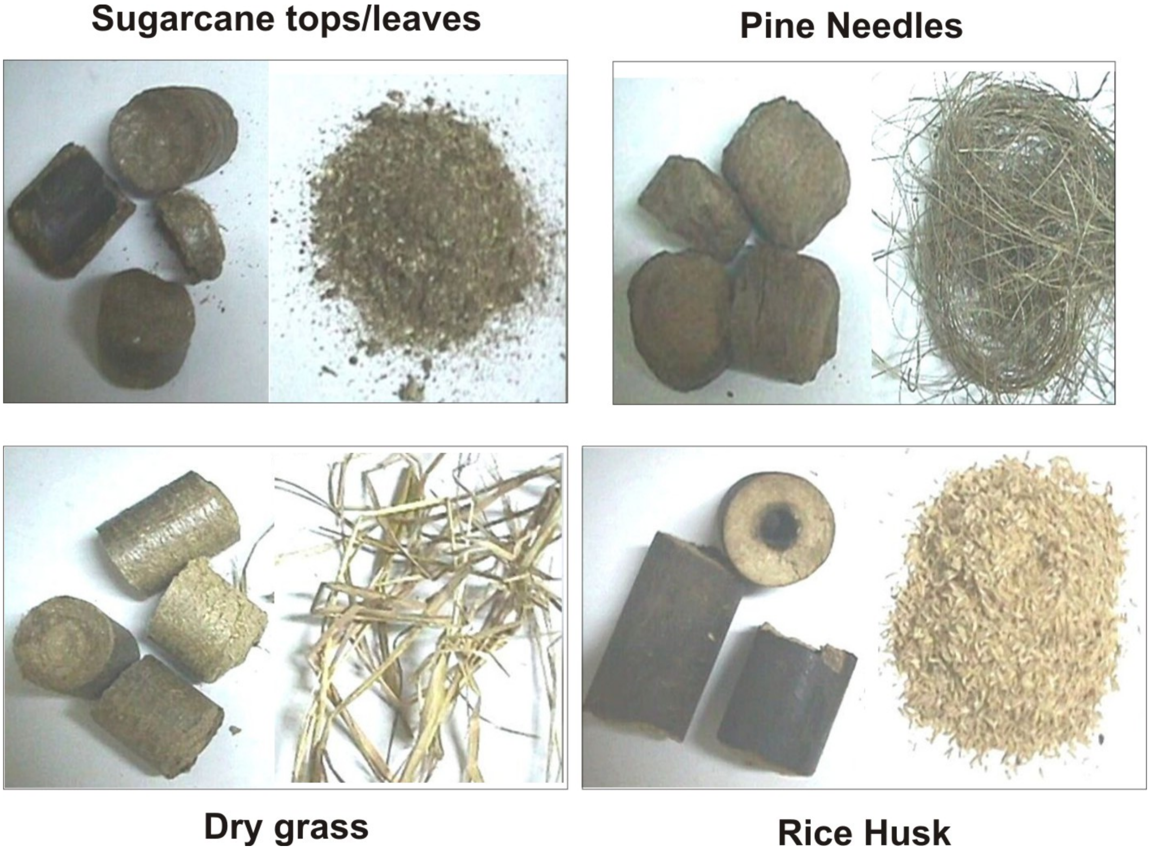

Figure 4.2: Pictures of sugarcane tops, pine needles, grass and rice husk all dried, pulverized and briquetted

Table 4.2: Structural, element composition of biomass (Cel, H-C, Lig, C-P, and Ash refer to mass percentages of cellulose, hemi-cellulose, lignin, crude protein and ash: The next four columns refer to the mass percentages of the elements, C, H, O and N)

Species	Cel	H-C	Lig	C-P	Ash	C	H	O	N
Cellulose	100	0	0	0	0	44.4	6.2	49.4	0.0
Corncob	40.3	26.9	16.6	15.4	0.8	47.2	6.7	43.2	2.1
Coconut shell	36.3	25	28.7	9.3	0.7	50.4	6.7	40.7	1.5
Eucalyptus	45	19	31	4	1.0	51.0	6.6	40.8	0.6
Subabul wood	40.8	24	24.7	9.7	0.8	49.4	6.6	41.6	1.6
Pinus-Sivestris	40.0	28	28	3	1.0	49.8	6.6	42.1	0.4
Corn stalks	42.7	23.6	17.5	9.8	6.4	45.1	6.2	40.7	1.6
Grundnut shell	35.7	18.7	30.2	10.3	5.1	49.1	6.4	37.8	1.6
Bagasse	41.3	23.8	18.3	13.7	1.5	48.0	6.6	41.6	2.3
Rice husk	31.3	24.3	14.3	8.4	20.0	37.4	5.2	34.3	1.3
Rice straw	35.0	21.7	12.6	11.1	19.6	38.0	5.4	35.2	1.8
Wheat straw	30.5	28.9	16.4	13.4	10.8	42.7	6.0	38.4	2.1
Millet husk	33.3	26.9	14	10.8	15	40.2	5.7	37.3	1.8

Table 4.3: Element composition and chemical formula of biomass (continued from the previous table: The first four columns refer to the mass percentages of the elements, C, H, N and O. The next three columns refer to the values of subscripts h, o and p in $CH_hO_oN_n$)

Species	C	H	O	N	h	o	n
Cellulose	44.4	6.2	49.4	0.0	1.67	0.833	0.0
Corncob	47.2	6.7	43.2	2.1	1.69	0.679	0.079
Coconut shell	50.4	6.7	40.7	1.5	1.60	0.607	0.051
Eucalyptus	51.0	6.6	40.8	0.6	1.55	0.599	0.029
Subabul wood	49.4	6.6	41.6	1.6	1.62	0.633	0.055
Pinus-Sivestris	49.8	6.6	42.1	0.4	1.59	0.634	0.015
Corn stalks	45.1	6.2	40.7	1.6	1.66	0.677	0.057
Grundnut shell	49.1	6.4	37.8	1.6	1.57	0.577	0.076
Bagasse	48.0	6.6	41.6	2.3	1.67	0.664	0.079
Rice husk	37.4	5.2	34.3	1.3	1.68	0.687	0.047
Rice straw	38.0	5.4	35.2	1.8	1.69	0.692	0.070
Wheat straw	42.7	6.0	38.4	2.1	1.69	0.674	0.064
Millet husk	40.2	5.7	37.3	1.8	1.70	0.696	0.055

Table 4.4: Mean mol wt for a given gas composition (mole fractions)

Species	X_i	$\mathscr{M}_i$	$X_i\mathscr{M}_i$
N_2	0.670	28	18.760
CO_2	0.161	44	7.064
H_2O	0.144	18	2.592
CO	0.013	28	0.364
O_2	0.005	32	0.160
H_2	0.002	2	0.004
NO	0.002	30	0.060
OH	0.003	17	0.051
Σ	1.000	-	($\mathscr{M}$) 29.055

Y_O = 0.4937. This gives h = 12 x 0.0619/0.4444 = 1.666, o = (12/16) x (0.4937/0.4444) = 0.833, n = 0. This gives the molecular formula for cellulose as $CH_{1.66}O_{0.833}$ = $C(H_2O)_{0.833}$. This is the same as the formula $C_6(H_2O)_5$ presented earlier. The subscripts on the chemical symbols are called the moles of that element. They represent the gram equivalent of that element. For example 1, mole of carbon is 12 g, one mole of hydrogen atom is 1 g and a hydrogen molecule is 2 g, one mole of oxygen atom is 16 g and 1 mole of water as gas is 18 g. The molecular formula represents a volumetric composition with fractions denoted by X_i (which denote the ratio of partial pressures to total pressure in a gaseous mixture or ratio of moles of the species to the total number of moles) and mass fractions, Y_i, refer to the mass fraction of these elements. These two are related by $X_i\mathscr{M}_i = Y_i\mathscr{M}$ where $\mathscr{M}_i$ and $\mathscr{M}$ refer to the molecular weights of specie i and the average molecular weight of the mixture. For a typical composition shown subsequently (see Table 4.6), the average molecular weight works out to 29.055 as shown in Table 4.4 with details of the calculation. If one knows the mass fractions of various species, then the avearge molecular weight is obtained from

$$\frac{1}{\mathscr{M}} = \frac{1}{\Sigma \frac{Y_i}{\mathscr{M}_i}} \tag{4.1}$$

4.4 Stoichiometric ratio and elemental composition

We can determine the amount of oxidizer needed to complete the combustion of a given substance if we know how much of each of the elements is present. The principal feature is that for air as the oxidizer (or oxygen as the oxidizer) carbon gets oxidized to carbon dioxide and hydrogen to water. In these reactions, mass must be conserved (first law of thermodynamics). Thus the oxidation of carbon, hydrogen and methane (a hydrocarbon) is expressed by

$$C + O_2 \rightarrow CO_2$$
$$H_2 + (1/2)\,O_2 \rightarrow H_2O$$
$$CH_4 + 2\,O_2 \rightarrow CO_2 + 2H_2O$$
$$CH_4 + 2\,O_2 + 2\;79/21\;N_2 \rightarrow CO_2 + 2H_2O + 2\;79/21\;N_2$$

The first reaction can be stated in words as: one mole of carbon reacts with one mole of oxygen molecule to give one mole of carbon dioxide. This will be a volumetric statement. Stated in mass terms, 12 g of carbon reacts with 32 g of oxygen to give 44 g of carbon dioxide. One can see that the final mass is the same as the total initial mass.

The second reaction can be stated as: one mole of hydrogen molecule reacts with half a mole of oxygen molecule to lead to one mole of water molecule. Stated in mass terms, 2 g of hydrogen reacts with 16 g of oxygen to lead to 18 g of water molecule. Here again mass conservation is obeyed.

The third reaction can be stated somewhat similarly. The fourth reaction is different from the previous ones due to the addition of nitrogen. In fact the composition of the oxidant is that of air. Nitrogen is usually inert and largely remains so for stoichiometric purposes (at combustion temperatures, NO gets formed at ppm levels).

It must be noted that there is no molar balance even though in some cases like for methane reaction the number of moles remains unchanged. In general, the volume changes when we move from reactants to products; sometimes decreases like in the above two cases, other times increases as it happens with dissociation (in the reactions, $H_2 \rightleftharpoons 2H$, $O_2 \rightleftharpoons 2O$, called dissociation reactions, the number of moles increases). This behavior has an effect on the combustion processes at constant volume; decrease in the moles contributes to decrease in pressure and increase in moles contributes to increase in pressure.

4.4.1 Stoichiometric ratio (S)

How much of oxidizer is needed to completely consume the fuel? It is taken that the final products in a combustion process are those in which the fuel elements are oxidized to stable products at ambient condition. This means hydrogen oxidized to water and carbon to carbon dioxide. The mass ratio of oxidizer required to complete the combustion to the fuel is called stoichiometric ratio denoted by S here. In the first reaction of carbon oxidation, S is obtained as 32/12 = 2.667. In the second reaction of hydrogen oxidation, it is 16/2 = 8. Thus it requires more oxygen mass to oxidize a unit mass of hydrogen compared to that of carbon. In the third reaction it is 64/16 = 4.

Suppose we change the oxidizer from oxygen to air. What is the modification to S?

The amount of oxygen in air is 20.95 % approximated to 21 % by volume and is 23.2 % by mass. As an approximation we take the rest as nitrogen - 79 % by volume and 76.8 % by mass. (in reality, there is 0.93 % Argon by volume and 0.69 % by mass). Thus 1 kg of oxygen is contained in 1/0.232 = 4.31 kg of air (or 4.31 kg of air contains 1 kg of oxygen and 3.31 kg of nitrogen). For the combustion of carbon with air, the value of S = 2.667 $\times$ 4.31 = 11.5. Similarly for hydrogen, S = 8 $\times$ 4.31 = 34.5 (see Table 4.5). To express these simply, one needs 11.5 and 34.5 kg of air to burn up 1 kg of carbon and hydrogen respectively. A hydrocarbon has a composition between carbon and hydrogen and therefore needs a magnitude of air between the two. Typically, 1 kg methane requires 17.2 kg air and 1 kg kerosene requires 14.6 kg air. These numbers are closer to those of carbon because carbon contributes to the mass of these substances much more than hydrogen.

We have discussed the value of S in mass units. Generally, liquids and gases are discussed in terms of volume units. What we need to do is to divide the mass numbers by the density ratio.

Densities of gases and liquids

The density of air is dependent on the ambient temperature and pressure governed by the equation of state: $p = \rho_{gas}\mathscr{R}/\mathscr{M}T$ where p = pressure in Pascals, ρ_{gas} is the density of the gas in kg/m^3, $\mathscr{R}$ is the universal gas constant (8.314 $J/g-moleK$), $\mathscr{M}$ is the average molecular weight of the gas and T is the temperature (K). The sea level pressure is taken as standard. This is 1 atm = 0.101325 MPa (Mega Pascal).

Ambient temperature standard varies; some use 0°C, others use 15°C and the temperature in tropics hovers around 30°C (20 to 40°C). The molecular weight of hydrogen is 2, oxygen 32, and air 29. Lower the molecular weight, lower is the density. The density of air at 1 atm and 27 °C (300 K) is 1.177 kg/m^3. For any other pressure and temperature and gas one uses appropriate scaling. This is represented simply by

ρ_{gas} = $1.177 \times (300/T) \times (p/0.101325) \times (\mathscr{M}/29)$

Natural gas that is extensively used as a clean gaseous fuel is largely methane, but has some fraction of higher hydrocarbns depending on the gas well from where it is mined. The density of methane (CH_4) at 300 K and 1 atm is (1.177 x 16/29) = 0.65 kg/m^3. The density of hydrogen and oxygen for the same conditions are 0.081 and 1.3 kg/m^3.

Liquids fuels like kerosene, gasoline and diesel have densities lower than for water. They are not pure compounds and hence their density depends on the processing to which the petroleum crude is subject to. Typically, the densities are 700 (gasoline), 800 (kerosene) and 850 (diesel) kg/m^3.

The data on the stoichiometric ratio of various fuels discussed till now is set out in Table 4.5. Hydrogen demands the largest amount of air. For most biomass S falls between 5 to 6 with deviations largely related to the ash content in the biomass. This value is less than half of that of diesel. It is 25 to 30 % lower than of Indian coal with 30 % ash. It will be almost 50% lower than for bituminous coal. This needs to be kept in mind when changes of furnace to operate on biomass are made. Also the fraction of volatiles in biomass is much higher than in coal; consequently, managing the power (or burn rate) needs attention.

4.5 Heat of combustion and heat of formation

The energy released in combustion is called the heat of combustion. For biomass it is a function of ash and moisture fractions. It is measured in a laboratory using a bomb calorimeter. There

Table 4.5: Elemental composition and the stoichiometric ratio for combustion with air of many biomass along with some reference values for some select compounds, all values in weight %

Species	C	H	O	N	Ash	S
Hydrogen, H_2		100				34.8
Carbon, C	100					11.4
Indian coal	57	5	7	1	30	8.7
Biomass char	90	2	3	0.5	4.5	10.9
Methane, CH_4	75	25				17.2
Diesel, $CH_{1.7}$	90	10				14.3
Cellulose	44.4	6.2	49.4	0.00	0	5.10
Corncob	47.2	6.7	43.2	2.1	0.8	5.76
Coconut shell	50.4	6.7	40.7	1.5	0.7	6.23
Eucalyptus	51.0	6.6	40.8	0.6	1.0	6.33
Subabul wood	49.4	6.6	41.6	1.6	0.8	6.05
Pinus-Sivestris	49.8	6.7	42.1	0.4	1.0	6.19
Corn stalks	45.1	6.2	40.7	1.6	6.4	5.81
Grundnut shell	49.1	6.4	37.8	1.6	5.1	6.04
Bagasse	48.0	6.6	41.6	2.3	1.5	5.82
Rice husk	37.4	5.2	34.3	1.3	20.8	4.91
Rice straw	38.0	5.4	35.2	1.8	19.6	4.62
Wheat straw	42.7	6.0	38.4	2.1	10.8	5.25
Millet husk	40.2	5.7	37.3	1.8	15.0	5.74

are two ways of expressing the heat of combustion. These are the higher heating value (HHV) and the lower heating value (LHV) or more conventionally lower calorific value (LCV). The higher heating value is obtained when the water vapor (really as gas) that comes out as a product is condensed to water at ambient conditions. The lower heating value is obtained when the water vapor is allowed to escape as vapor. The energy released in the condensation of water vapor to water as a liquid makes the HHV higher than LHV. What is more relevant to practical combustion situations is the lower heating value since the water vapor will escape with the burnt gases from the system to which heat is being transferred. To simplify matters we recognize that on an ash-free and moisture-free basis the biomass composition does not have much variability. It is perhaps instructive to look at the decomposition of the calorific value in terms of structural components. The LCV of cellulose, hemicellulose, lignin and extractives/oils (moisture-free conditions) are 16.4, 16, 20 - 24 and 34 - 36 MJ/kg of individual components. It appears that the LCV of cellulose [$C(H_2O)_{0.833}$] and hemi-cellulose [CH_2O] are about the same. Lignin whose precise structure varies has more carbon [$CH_{0.8}(H_2O)_{0.65}$ is one such structure] and has therefore a higher LCV. Extractives and oils have a composition closer to hydrocarbons and therefore have an LCV of fossil fuels. There have been many studies on finding a simple correlation for the LCV of biomass (an internet search reveals dozens of studies]. Based on the experimental studies at the laboratory and using the inputs described above the correlation is set out as

$$\text{LCV (MJ/kg)} = 18.0\,(1 - f_{ash}) - 20\, f_w$$
$$\text{for all } f_{ash} = \text{ash fraction, 0 - 20 \% and } f_w = \text{moisture fraction, 0 - 50 \%}$$

The values of LCV obtained from such a correlation are valid to within ± 5 %. The values of HCV will be larger by 7 %. For wood that is sundry (moisture fraction $\sim$ 10 %) with an ash content of 1 %, the LCV is 15.8 MJ/kg. There is another quantity called the heat of formation. It is defined with respect to a species. It is defined as the heat of combustion when the species alone is the reactant and stable products at ambient condition are the only products. A table of these heats of formation are composed using the heats of combustion in a manner that the data are consistent (see any book on combustion in the references at the end of this chapter). Using the heats of formation of carbon dioxide and water (in gaseous state) the heat of formation of biomass can be obtained as HoF [$C(H_2O)_{0.7}$] = - 6.8 kJ/kg. The importance of working with heat of formation is that if the intial conditions of combustion are changed, like for instance, biomass is being burnt with heated air and one wants to obtain the adiabatic flame temperature and composition, it will turn out that use of heat of formation is a straightforward and convenient approach.

4.6 Gas Composition at high temperature

The reactions noted above will occur more vigorously at higher temperatures because the energy contained in the species as reflected in the random velocities of the molecules and the atoms will become larger. This causes the stable molecules to decompose (or dissociate as it is termed) into smaller fragments. If we take hydrogen gas the fraction of hydrogen atoms will become higher with temperature - for instance, at 1% dissociation, the temperatures are 3590 K for N_2 to 2N, 2570 K for O_2 to 2O, 2430 K for H_2 to 2H, around 2100 K for H_2O to either H_2 + (1/2) O_2 or OH + (1/2) H_2 and 1930 K for CO_2 to CO + (1/2) O_2. This order, it can be noticed, is in terms of decreasing difficulty of dissociation. The fact that N_2 almost just does not dissociate unless temperatures are very high is the reason for it not reacting with O_2 leading to a stable desirable atmosphere at ambient conditions; otherwise, there would be considerable amount of oxides of nitrogen and living would be impossible. Dissociation of *CO_2 seems the least difficult* and this is why in combustion reactions, conversion of CO to CO_2 would turn out to be difficult; the reaction favors the presence of CO at combustion temperatures in undesirable amounts, small they may be. This is also the reason why catalytic converters are fitted on to engine exhausts to help limit the CO exhausted into the atmosphere. When reactions occur, *the same elemental composition* - C, H, N, and O expresses itself in various forms of species with different compositions at increasing temperatures. The flame temperatures are expected to be in the range of 1800 to 3000 K for the cases of interest here. At lower temperatures that may be created by moderately exothermic substances like biomass burning with air, the products will contain the most stable products like H_2O, CO_2 and N_2 with little CO, OH, NO, H and O, the list here being ordered in terms of decreasing order of presence. If oxygen is used as the oxidant as may happen in some applications, the flame temperatures will be sufficiently high and many radicals will be found in fractions that are not too small.

When we burn any fuel with air, one can do so with air less than, equal to or more than the requisite amount of air. This is described by a quantity called equivalence ratio, ϕ. It is the ratio of fuel-to-air to fuel-to-air at stoichiometry, a condition at which air is just sufficient to produce complete products of combustion. It is written as

ϕ = (fuel/air)/(fuel/air)$_{\text{stoichiometry}}$, ϕ = 1 means stoichiometric condition

With $\phi < 1$, it is lean operating condition and $\phi > 1$ is rich condition.

The question of determining the composition of a gas mixture with fuel and air undergoing chemical reaction at any high temperature is to be first understood before determining the flame temperature. This question is posed this way. Given a CHNO composition that contains both fuel and oxidizer components and a set temperature, say 1800 K and pressure, say 1 atm what would be the composition after equilibrium is allowed to occur. The word equilibrium means that sufficient time is given for the reactions to get completed in the combustion chamber.

We start with fuel like wood with a CHNO composition such as $CH_{1.5}O_{0.6}N_{0.029}$. When the wood is burnt with the right amount of air (just stoichiometric), the temperatures attained will be typically 2000 K. At these temperatures, as a first approximation, it would be good to assume that the products would be CO_2 and H_2O. Thus,

$CH_{1.5}O_{0.6}\ N_{0.029} + 1.075(O_2 + 3.76N_2) \rightarrow CO_2 + 0.75\ H_2O + 2.0065N_2$

When this composition is known, we can compute the flame temperature (T_f) for the above stoichiometric combustion process by the procedure outlined below. If the air supplied is more than this, for a condition called "lean combustion" we can write

$CH_{1.5}O_{0.6}\ N_{0.029} + (1.075 + z)(O_2 + 3.76N_2) \rightarrow CO_2 + 0.75\ H_2O + 2.0065N_2 + z(O_2 + 3.76N_2)$

The excess air is left behind in the products also. It contributes to reduction in flame temperature because it absorbs heat. This ensures that any possible deviation from the above composition is minimal.

For $\phi > 1$, the "rich combustion" there will be incomplete combustion. The products will not be limited to the ones seen in the above equation. Some amount of CO, H_2 and other complex compounds will be produced. The degree of complexity of the products will increase as combustion becomes rich.

For the lean and stoichiometric conditions, the reacting elements are C = 1, H = 1.5, O = (0.6 + 2.15 + 2 z) = 2.75 + 2 z and N = 3.76 x 2 x (1.075 + z) = 8.084 + 7.52 z. For these elements and a certain temperature (as 2000 K above) and pressure (as 1 atm noted above), the composition at high temperature will contain CO_2, H_2O and other species such as CO, OH, H, and O. To compute this composition at a set temperature, one needs to set up an element balance for each of the elements (C, H, O, N etc) and a set of equations called equilibrium relations that result from the fact that the reactions that take place between various species will reach equilibrium; at this stage a quantity called Gibbs free energy for constant pressure reactions or Helmholtz free energy function for constant volume reactions attains a minimum. This condition allows relationships between different species be established through a minimum set of equilibrium reactions. Solution of element conservation relations and equilibrium relations provides the values for mole or mass fractions of all the species at equilibrium.

The subject of determining equilibrium composition has been addressed by several researchers over a period. Several software tools have been made available. One of the more standard tools is a code documented in NASA SP 273 and used widely. This code gives results even for rich conditions. However, the results are not realistic beyond some "richness" because all the species reached at equilibrium will not be found. The phenomenon will largely be "rate controlled" and the speed of the reactions will matter in observed composition.

4.7 The flame temperature

Accurate calculation of flame temperature for any set of reactants and initial conditions - temperature and pressure (or volume) is a two-stage process. The first aspect is to enable a calculation of the gas composition at any specific pressure and temperature. This is done by a method described in the previous section. The second part is to strike an enthalpy or energy balance such that the energy released in the reactions is absorbed by the species found at high temperature from the ambient to the high temperature chosen. When the match between the energy released and energy absorbed takes place, the system can be taken to be adiabatic and the derived temperature will be the flame temperature. If the chosen temperature is higher than the true value, the difference between the energy released and energy absorbed will be negative. The opposite will be true for the chosen temperature being lower than the true value. Thus an iterative scheme is used to obtain the final value.

For cases where the composition at high temperature is assumed or known, the calculation is simpler. It is simply a one-step procedure. Determine the temperature at which the enthalpy rise of the products equals the released enthalpy. Since the specific heat of gases increases with temperature, even this scheme may involve iteration. But admittedly it is lot simpler than the full scale scheme involving calculation of the composition at high temperature several times.

We will now make a simple estimate of the flame temperature for wood with the composition noted above. The heat of combustion at 10 % moisture is 16 MJ/kg, fuel. The reaction for this is written as

$CH_{1.5}O_{0.6}N_{0.029}$ + 0.153H_2O + 1.075(O_2 + 3.76N_2) → CO_2 + 0.75H_2O + 4.0163N_2 + 0.153 H_2O (vapor)

$$27.5\ kg\ \text{(dry fuel)} + 2.75\ kg\ \text{(water)} + 147.4\ kg\ \text{(air)} \rightarrow 177.6\ kg\ \text{(product)}$$

Treating constant pressure specific heat as constant (independent of temperature which it really is not), we can write the enthalpy balance as

177.6 kg × c_p kJ/kg K × (T_f - 300) K = 16000 kJ/kg x 30.25 kg

where the left hand side represents the amount of heat absorbed and the right hand side, the amount of heat released.

The specific heat of the gas mixture varies from about 1 kJ/kg K at 300 K to as high as 1.6 kJ/kg K at 3000 K.

If we choose mean c_p values of 1.3 and 1.4 kJ/kg K, we get T_f as 2396 and 2200 K respectively.

Calculations are made by using the NASA SP 273 code and the results for adiabatic flame temperature and equilibrium composition are presented in the Tables 4.6 and 4.7 for wood-air at 0 and 10 % moisture fractions and for wood-oxygen at 0 and 30 % moisture fractions (moisture fractions measured against dry wood) at three equivalence ratios. The chosen composition of wood is shown at the bottom of the tables. Some amount of potassium is included as an inorganic element in wood but other inorganic elements are also present in wood or other biomass. The composition is expressed in terms of volumetric fractions (also termed mole fractions) or ratio of partial pressures with total pressure. The peak flame temperature at ϕ = 1 for dry wood is 2194 K. The drop in peak temperature is about 50 K for 10 % mositure. The composition at the lowest temperature (at ϕ = 0.7) is close to the simple assumption made earlier. At stoichiometry, the significant deviation in composition from simple chemistry arises from CO.

The results for wood - oxygen are important from the point of view of generating syngas. A composition that has H_2:CO ratio of 2:1 is desired. To get this and manage it at lower temperatures, one generally introduces steam. An alternate approach is to use wet wood to reduce the efforts of drying required in the gasification process. Wood with 30 % moisture with oxygen has been considered in the calculations shown in Table 4.7. The flame temperatures (T_f) are indeed very high even at 30 % moisture - 2747 K. At these temperatures dissociation is significant and therefore one finds larger fraction of several radicals. Even so, the H_2:CO ratio is still around 1:3 as with wood - air mixture at fuel rich conditions (ϕ = 1.3). Achieving desired composition may require much higher fuel richness than the value indicated here. Under these conditions the processes may become reaction rate controlled and hence the composition will be different from those expected at equilibrium.

Table 4.6: T_f and equilibrium composition (mole fractions) for wood with *air* at p = 1 atm and $T_{initial}$ = 300 K

	Dry wood			Wood,10% moisture		
ϕ	0.7	1	1.3	0.7	1	1.3
T_f (K)	1850.0	2193.9	2042.1	1802.3	2140.7	1961.3
N_2	0.706	0.670	0.617	0.693	0.656	0.598
CO_2	0.127	0.161	0.127	0.125	0.159	0.128
H_2O	0.108	0.143	0.154	0.124	0.166	0.176
CO	0.0	0.013	0.071	0.0	0.009	0.073
O_2	0.055	0.005	0.0	0.054	0.004	0.0
H_2	0.0	0.002	0.029	0.0	0.002	0.023
K	0.0	0.0	0.001	0.0	0.0	0.001
KOH	0.001	0.001	0.001	0.001	0.001	0.001
NO	0.002	0.002	0.0	0.002	0.001	0.0
OH	0.001	0.003	0.0	0. 001	0.002	0.0

Wood: $CH_{1.7}N_{0.0053}O_{0.79}K_{0.007}$

Table 4.7: T_f and equilibrium composition (mole fractions) for wood with O_2 at p = 1 atm and $T_{initial}$ = 300 K

	Dry wood			Wood, 30% moisture		
item	0.7	1	1.3	0.7	1	1.3
T_f (K)	2868.2	2910.4	2884.3	2707.5	2737.0	2665.6
CO_2	0.268	0.253	0.224	0.273	0.266	0.238
H_2O	0.269	0.305	0.326	0.394	0.443	0.468
CO	0.118	0.198	0.269	0.067	0.123	0.181
O_2	0.208	0.092	0.032	0.171	0.062	0.012
H_2	0.017	0.033	0.055	0.014	0.030	0.054
K	0.001	0.002	0.002	0.001	0.001	0.001
KOH	0.001	0.001	0.001	0.001	0.001	0.001
N_2	0.000	0.001	0.001	0.001	0.001	0.001
NO	0.001	0.001	0.0	0.001	0.001	0.0
OH	0.070	0.067	0.050	0. 054	0.048	0.027

Wood: $CH_{1.7}N_{0.0053}O_{0.79}K_{0.007}$

4.8 Theoretical vs. Measured flame temperature

The theoretical temperatures when wood burns with air is 2200 K. However, when wood is burnt in stoves working with air supplied by free convection, one rarely gets to such temperatures. The reported temperatures rarely exceed 1200 K. One tends to think that theory is unrealistic. In this context, it is useful to examine as to what extent does theory replicate reality [Mukunda, 2009], for it is often thought that theory is always very distant from reality. The word “theoretical” itself has several levels. The first is the adiabatic flame temperature. This does not involve flow aspects. The next aspect includes fluid flow effects that influence the flame temperature through stretch (or straining of flame surfaces). Thirdly, there are heat losses by the system with flame to the surroundings. Inference from flame temperature measurements should account for these aspects. When it is asked whether the adiabatic flame temperature computed by the procedure outlined earlier is realized in actual practice, it is to be understood that stretch effects are excluded. What is this quantity called stretch that we are talking of? One can expect that in a complex flow field, the fluid elements will move in various directions. A flame is expected to be stretched if there is change in fluid velocity in a direction parallel to the flame surface. One also talks of strain rates somewhat synonymously. This stretch can be positive or negative. Positive stretch makes the flame thinner. Negative stretch makes the flame thicker. When a flame is flat and the *premixed fluid* flows through the flame in a direction normal to it, one would have an *unstrained* flame. In a classical Bunsen flame, the region near the top where the flame is curved, one experiences negative stretch (also called compressive strain rate) and the conical region below this segment experiences positive stretch. In a complex flow field, the flame surface could move unsteadily and curve up in various directions, leading to various strains being imposed on the flame. If one measures the temperature in the burnt zone just after a flat flame, one would really measure the adiabatic flame temperature corresponding to the *mixture ratio of premixed mixture*. If one measures the properties in a conical (Bunsen) flame one will find the effect of stretch is to reduce the “flame speed” or the local consumption rate and at extreme stretch, there could be flame extinction as well. If the flame is turbulent, one could have flame extinction at several locations at different instants leading to temperature fluctuations from the ambient value to high temperature largely because of these effects.

The effect of heat losses will be severe in small systems and lesser in larger systems - the governing factor would be a geometry which minimizes the surface area that contributes to heat loss but has necessary volume to release the heat. Such a geometry is essentially a sphere. Increasing the combustion throughput or power in such a spherical combustor reduces the role of heat loss in determining the peak temperature achieved in the combustor. The heat losses can contribute to the observed reduction in temperature by a few hundred Kelvin.

Thus, both the above factors can reduce the observed temperatures in actual systems by several hundred Kelvin. Experiments on modern day stoves (to be discussed later) have shown that in relatively small systems, by a suitable adjustment of air-to-fuel ratio, one can get 1650 K. Inevitable heat losses contribute to the reduction from the theoretical maximum.

4.9 Can we raise the peak temperature from a given reactant set?

For thermal applications like ceramic furnace where some operations require 1600 K, one uses fuel oil burner usually even when there is an option of using biomass based combustion source. This is because biomass based combustion device does not usually lead to gases at this temperature. Also, the problem is accentuated due to the use of wood with moisture. However, very

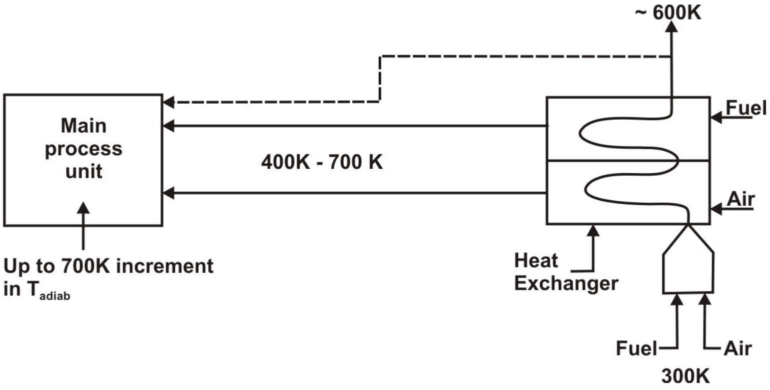

Figure 4.3: Schematic of an arrangement to raise the peak temperature of a fuel–oxidizer combination

genuinely, the temperatures attained in actual systems with biomass, even if it is dry rarely reaches such high temperatures. It is also possible to ask a question - can biomass or charcoal be used for furnaces to melt iron or steel that require about 1850 K. If we are using a fuel–oxidant mixture that generates say, 1200 K, how can we achieve the objectives noted above? Figure 4.3 shows the schematic of how this can be achieved. The fuel–oxidant mixture is burnt in two locations, with the hot gas from the first location being used in a heat exchanger to pre-heat the oxidant alone or the fuel as well before being used in the second combustion system. Since the entry conditions for the second combustion system have reactants at sufficiently high temperature (even up to 800 K depending on the quality of the heat exchanger), it is possible to raise the temperature even up to 1900 K. In many practical situations, the waste heat from the process itself can be used for preheating the reactants, either in part or completely. This is true for many metal melting industries designed and built at a time when fuel was considered cheap and the burnt gases were simply sent up into the atmosphere. By putting up a heat exchanger to heat the air for combustion, such industries would have derived enormous financial benefit and would have saved the planet considerable fuel! Of course, they can effect the changes any time they decide to do.

4.10 Biomass and fossil fuel properties

It is important to appreciate the properties of biomass vis-a-vis those of fossil fuels because in practice, one will be faced with situations where the change from fossil fuels to solid bio-fuels will be looked for due to lower costs of these fuels in comparison to fossil fuels. These are summarized in Table 4.8. The calorific value of wood is about 37% of diesel. While diesel is perhaps a desirable alternative, for heat applications, furnace oil (fuel oil) is the one most often used in industries. Fuel oil has a calorific value about the same as diesel. This means that to provide the same total heat input one needs to burn up wood of 2.7 (1/0.37) times the throughput of diesel. By this logic, a 10 kg/h of diesel usage can be replaced by 27 kg/h of wood or 34.6 kg/h of rice husk provided the application does not demand temperatures more than about 1400 K. If the application demands more than this temperature, one can use the strategy outlined earlier (in section 4.9) or suitable addition of diesel/furnace oil is needed. The latter solution is usually what becomes acceptable since existing diesel/furnace oil based burners will get fitted with dual-fuel burners that can used in any appropriate mode as required without loss of operational reliability. In a period of rising fossil fuel costs, alternatives based on agro-

Table 4.8: Stoichiometric ratio, heat of combustion and flame temperatures of fuels, * = gas at ambient conditions and liquid at > 3 atm

Fuel	Mol. Formula	state	Ash %	S_{air}	H_{comb} MJ/kg	T_f K
Wood, sundry	$CH_{1.6}\ O_{0.71}$	Solid	1	5.9	15.8	2100
Rice husk, sundry	$CH_{1.7}\ O_{0.69}$	Solid	20	4.9	12.4	1800
Diesel	$CH_{1.7}$	Liq	0	14.3	43.0	2300
LPG	$CH_{2.4}$	Gas/Liq*	0	15.3	45.0	2300
Natural gas	$CH_{3.8}$	Gas	0	16.5	49.0	2300

reisudes become very attractive even with this ratio of biomass-to-fossil fuel for delivering the same heat. It is useful to recognize that biomass costs even in rural markets keep rising when the fossil fuel prices rise and the cost of fossil fuel-to-biomass is between 6 to 8. Biomass alternatives become attractive for heat generation, in fact more than for electricity since its prices are state regulated.

4.11 Combustion of solid bio-fuel and emissions

The combustion process of solid fuels involves several steps since the flame that will be the final result is only in the gaseous phase. After ignition of the fuels, something that involves a process of heat up of the fuels to about $> 600°C$, gaseous fuel components emerge from the solid fuel. The gaseous fuel components consist of CO, H_2, CO_2, H_2O and other complex oxygenated hydrocarbons that when condensed to ambient temperature will become liquids called tar. This process is essentially pyrolysis. These gases mix with air around and react exothermically in the gaseous phase to release heat. This heat is transferred back to the surface of the solid fuel to release more volatiles are released. This process of volatile combustion will continue till all the volatiles are consumed. What remains then is char. Char is composed largely of carbon (some residual hydrogen is present). Typically this char will be red hot - temperatures of about 700 to 800°C and will react with oxygen of the surrounding air medium heterogeneously (surface combustion) with perhaps a blue gaseous flame (between carbon monoxide and oxygen of air). If sufficient residence time is provided for the high temperature reactions to occur and the oxidant is available around the fuel fragments, equilibrium temperature and composition of the fuel-air mixture will be attained. For mixing related limitations as well as system related heat loss, the final conditions will depart from the equilibrium conditions. The principal products of combustion are CO_2 and H_2O. There are other emissions as well and will be discussed subsequently.

4.12 Burn rate of solid fuels

Solid fuels are burnt in a variety of shapes and sizes as many of these are considered wastes. But in some European countries, wood stock is dried, pulverized and pelleted to make the fuel shape and quality uniform. Agricultural residues come in a variety of shapes sizes and moisture content and are used for combustion in boilers as well as cook stoves. The only way of reducing this enormous variation in shapes and sizes is to pre-treat the biomass by drying, pulverizing and then pelleting the fuels. This process may not produce fuels of identical composition, but of uniform shapes and sizes as well as moisture content all of which affect the combustion process in terms of efficient heat release as well as reduced emissions. Such fuels are burnt on the grate as well in a suspended mode in fluidized bed combustion systems. A very general and powerful way of approaching the subject of determining the burn rate is to strike a heat balance at the surface of the fuel. It is $\dot{m}''_f \Delta h_s$ = q''_g where $\dot{m}''_f$ is the mass flux from the fuel surface, Δh_s is the heat of phase change at the surface and q''_g is the heat flux from the gas phase. The dynamics of the gas phase heat transfer process depends on the geometry (in this case, diameter) and fluid flow outside of the sphere. Thus the mass flux is directly proportional to the heat flux to the first order. The implication of this simple feature is very significant and is not adequately appreciated. If we take two identical pieces of wood (say, a sphere) of different densities, one say twice the other, the mass flux is the same for both the wood spheres implying that the sphere whose density is twice that of the other will burn twice as long. This means that the burn time during the flaming phase ($t_{flaming}$ varies directly as the density of the fuel, ρ_w). This explains a commonly observed feature that "light fuels burn faster". The heat of phase change, Δh_s is most usually positive indicating endothermicity of the phase change. But some woods that have mild exothermicity (because it turns out that hemicellulose and lignin have exothermic reactions and cellulose has endothermic reactions in the phase transition regime), a separate theory needs to be worked out. This has been done by Mukunda et al (1984) and the results represent the reality in terms of overall combustion times well. Recently, Varunkumar et al (2010) have performed rigorous studies on the char sphere combustion. If we condense the results of these studies, we can set them out as

$$t_f = 7\rho_w d_w^{1.8} \tag{4.2}$$

$$t_{char} = 20\rho_{char} d_{char}^{1.8}[1 - 0.0045\frac{Re^{0.5}}{Gr^{0.25}}] \tag{4.3}$$

where t_f and t_{char} are the flaming and char burn times in s, ρ_f and ρ_{char} are the densities of biomass and char in g/cm^3, d_w and d_{char} are the diameters of wood and char spheres, Re is the Reynolds number based on the sphere diamter = $\rho_f U d_w/\mu$ and Gr is the Grashof number defined by $Gr = g[(T_s - T_0)/T_0]d_{char}^3/\nu^2$. These results can be used for pellets and other non-spherical biomass by using the volume based diameter (d_{eq} = $[6 \times volume/\pi]^{(1/3)}$).

For stagnation point flows over chars, Evans and Emmons have performed experiments and also performed analysis. They have chosen to treat the problem involving surface kinetics even though the results seem to show as diffusion limited (within the scatter of experiments). The results of the study correlate very well with $\dot{m}'' = 16V^{0.5}$ with the mass flux $\dot{m}''$ in kg/m^{2}s and the velocity, V in m/s. This expression can be recast in terms of Reynolds number as $\dot{m}'' = 0.75 \times 10^{-3} Re^{0.5}$ by noting that in their experiments the characteristic dimension (of the cylinder) is 27 mm.

Most large scale combustion systems in Europe use wood chips using a travelling grate or inclined grate (see below). In these cases, combustion proceeds with air flow from the bottom and the flame front proceeding from the top downwards normal to the fuel surface. In these cases, the ratio of the air mass flow rate to biomass consumption rate (as also fluxes) is fixed by gasification as 1.5 for dry wood chips. This constitutes 80 % of the mass loss of the fuel. The remaining 20% will get burnt as char far downstream on the travelling grate, again with fixed air-to-hot char consumption rates that will show an effective air flux-to-char mass flux of one-fifth to one-sixth of the raw biomass ratios.

Table 4.9: Typical boiler characteristics, TrG = Travelling grate, UW = Urban wood, Ag = Agricultural prunings, nuts, etc

Item	TrG-Stoker Grate 1	Straw boiler Grates 2,3	FBC - 1 Fluid bed	CFB 1,2	CFB 3
Capacity, MWe	20	5 - 12	27	28	18
Steam rate, t/h	84	26 - 40	116	118	77
Steam Pressure, atm	64	67	93	62	62
Steam temperature, °C	421	450	513	454	482
Furnace exit Temp, °C	850	640 - 760	960	882	900
Fuel	UW + Straw	Straw	UW + Ag	UW + Ag	UW + Ag
Biomass rate (dry), t/h	22	6 - 8	30	30	22

4.13 Large combustion systems

The development of large combustion systems is particularly relevant to countries where large amounts of agricultural residues are available for utilization. This calls for owning of large tracts of land by individuals or institutions. The development of large combustion systems based on agro-residues took place in the USA as a response to rising fossil fuel prices in the late seventies. The state of California provided financial benefits for prospective users of bioresidues for process steam or steam power. Consequently, many projects got developed in the early eighties in the USA (Miles et al, 1996). Table 4.9 shows the several types of combustion systems (used in conjunction with boilers) that were deployed for the use of agricultural residues and waste wood. Figures 4.4, 4.5 and 4.6 show the schematics of these combustion systems. Specifically, Fig. 4.4 is the schematic of travelling grate, Fig. 4.5 of inclined grate with straw and such materials and Fig. 4.6 of three types of fluidized bed and circulating fluid bed combustors.

In each of the various types, namely, (a) travelling grate-stoker type, (b) inclined grate (c) vibrating grate (d) bubbling fluid bed and (e) circulating fluid bed systems, there are several alternatives on the way air is supplied. Air can be sent through the grate uniformly or in sections in which larger air flow comes through the grate in the frontal area and much reduced flow in the downstream section to prevent low density char/ash blow off. Biomass is moved down ensuring burn-out by the time the end of the grate is reached. At this stage, it falls into an ash pit. Since air flow through the grate is around 30 - 40 %, the remaining air for combustion supplied much above the fuel bed to ensure gaseous combustion. This procedure helps limiting the excess air. This process can be likened to staged combustion with gasification as the first step along the movement over the grate. Thus, the basic processes involve managing a near uniform bed over the grate, air supply from the bottom to facilitate gasification and subsequent char gasification-combustion and substantial gaseous phase combustion with over-fire air. By managing the air flow over various segments along the grate, it should be possible to limit the gaseous and particulate emissions. Fluidized bed combustor is characterized by a bed of inert material like sand through the bottom of which flows air (in this case) at speeds of 0.5 to 3 m/s. This process causes bubbling of the air bubbles through the bed and the bed becomes expanded. Into this fluid is introduced biomass uniform in size generally. When the bed is heated by a suitable start-up procedure, combustion will occur stabilizing the bed temperature to a level set by the ratio of throughput of air-to-biomass. The intense movement of sand particles enhances the heat transfer to the biomass and maintains the bed at the temperature. In a few cases, the volatiles released here burn up above the bed (in a zone called freeboard). When the velocities that carry the sand and fuel are large - typically 5 to 10 m/s, the system operation transitions to circulating fluid bed reactor (shown on the right side of Fig. 4.6). Larger throughputs can be managed at the same diameter. The carry-over of particulate matter increases in magnitude

Table 4.10: Principal composition of ash of different biomass, all components are weight fraction of *ash*; only major fractions determined

Feature	Hog-wood fuel	Furniture waste	Rice straw	Wheat straw	Almond hulls
Ash, %	1.0	3.6	18.7	9.6	6.1
Chlorine	-	<0.01	0.6	1.8	0.02
SiO_2	35.2	57.6	74.7	37.1	9.3
CaO	26.4	13.9	3.0	2.5	8.1
K_2O	9.3	3.8	12.3	21.7	52.9
Na_2O	5.6	2.4	1.0	9.7	0.9
Al_2O_3	2.3	12.2	1.0	2.7	2.1
Fe_2O_3	4.4	5.6	0.9	0.8	0.8
MgO	7.6	3.3	1.7	2.5	3.3
P_2O_5	5.7	0.5	1.4	2.0	5.1
SO_3	3.0	1.0	1.2	4.4	0.3

from fixed bed systems (like travelling grate-stoker systems) through FBC to CFBC systems. Inevitably, particulate emission control systems are more heavily taxed in both FBC and CFBC systems.

In the usage of these systems by various investors in California, even before economic benefits were derived, serious operational problems of deposition in the boiler system were experienced extensively. This led to severe losses in the operation of industrial systems and a national team involving consultants, industrial experts and the national renewable energy laboratory (NREL, USA) was established (Miles et al, 1996). Consequent upon this, a very thorough study was undertaken. The most severe of the problems are (a) high temperature bonded deposits in the super-heater, (b) bridging and blockage of convection passes, (c) erosion of super-heater tubes, and (d) corrosion in the super-heater, air heater, and economizer. In addition other problems experienced were (i) deposits on refractory but not water-walls, (ii) accumulation around air tuyeres and refractory, (iii) fuel feeder blockage from slag, (iv) fluidized bed media agglomeration, blockage of gas passages by deposits and fine fuels being carried over and generating hot spots by after-burning. After a careful study, the problem was traced to the composition of the ash of the solid biofuels.

The composition of ash shown in Table 4.10 is instructive. While wood is shown with specific oxides, these can vary significantly amongst these constituents; the crucial issue is that the ash content itself is small and these become quite insignificant. That furniture waste differs from Hog-wood would have links with the waste picking up sand/grit from the working environment. Rice straw has significant silica and potassium oxide and larger fraction of phosphorous pentoxide. Rice husk has even more significant fractions of silica (95 % of the ash is SiO_2). The presence of silica is due to the plant growth process and the latter two arise due to uptake from fertilizer inputs. Wheat straw shows similar behavior except that potassium component is much larger. Almond hulls show the largest potassium and phosphorous components. The presence of K_2O and Na_2O is shown to be the root cause of ash fusion problems as the ash melt temperatures are brought down by them.

Such problems have also been experienced in a power generation system (Malavalli power station, Karnataka, India see *www.mpppl.com*) due to the use of sugarcane tops as the fuel. The deposit inside the boiler tubes was so heavy after 8 to 10 months of operation that the boiler tubes had to be replaced.

In general, the plants that wanted to use the residues anyway used a variety of methods to prevent or remove deposits, including fuel management, boiler control, cleaning and additives.

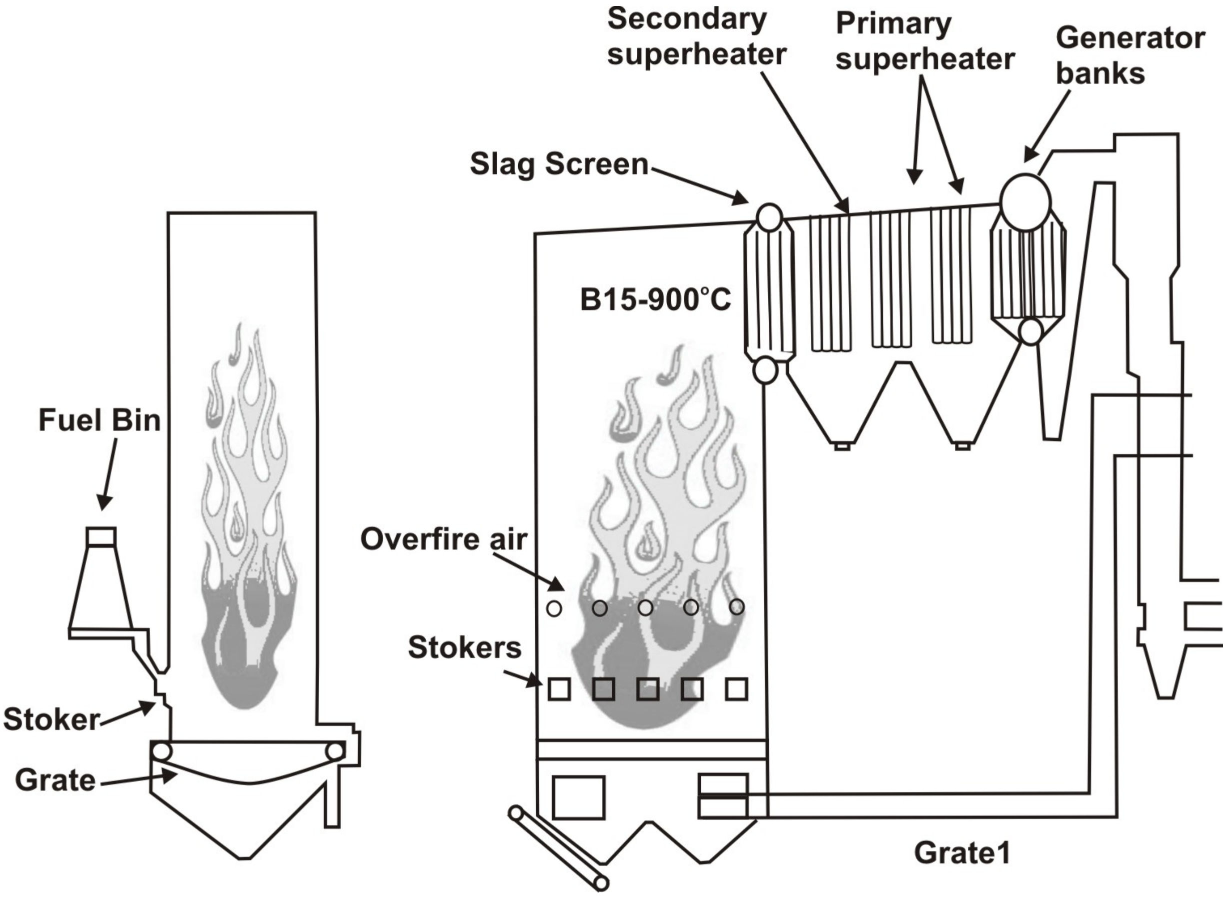

Figure 4.4: Commonly used boiler with combustion system based on cooled travelling grate used for biomass with airflow through the grate (from Miles et al. 1996)

Fuel management techniques were to eliminate the worst acting fuel components completely where possible, more usually, dilute the "dirty" fuels with clean fuels. Boiler control was also exercised to limit temperature excursions. Cleaning and additives included the addition of limestone based on boiler condition. The last strategy was used in a 10 MWe project at Jalkheri (Punjab, India) that was running the power plant on rice/wheat straws. There were claims of benefits from the use of limestone but the project that was shut down for 8 years was revived with modified equipment and other sources of fuel as well in recent times.

4.14 Gaseous emissions from solid fuel combustion devices

Apart from CO_2 and H_2O, CO, oxides of nitrogen (NO_x) and oxides of sulphur (SO_2) are also emitted to varying small fractions. Table 4.6 shows the composition at varying stoichiometries from lean to rich. Since the solid fuels have inorganic matter what will be left behind are these in the form of ash; some times some unconverted carbon will also be embedded in it. Because of the physical movement of the bed and air stream around, some of the carbonaceous ash will be fragmented. It has also a low density. Consequently, it will get carried away by the surrounding stream if the velocity is significant - typically this is >0.15 m/s.

Carbon dioxide, one of the principal products of biomass combustion is undesirable because

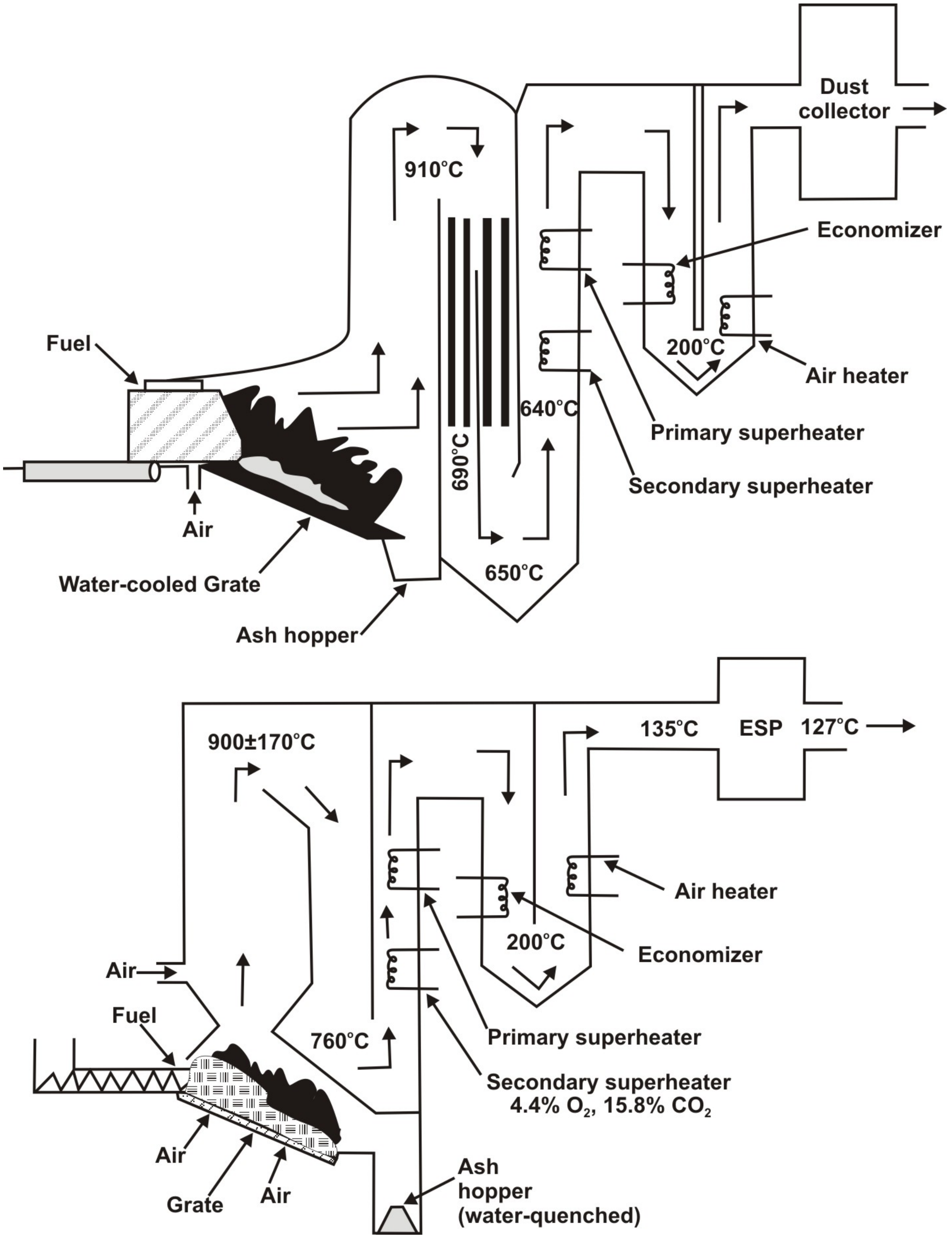

Figure 4.5: Boiler with two other combustion systems used for biomass; the biomass is gently pushed on a cooled grate (from Miles et al. 1996)

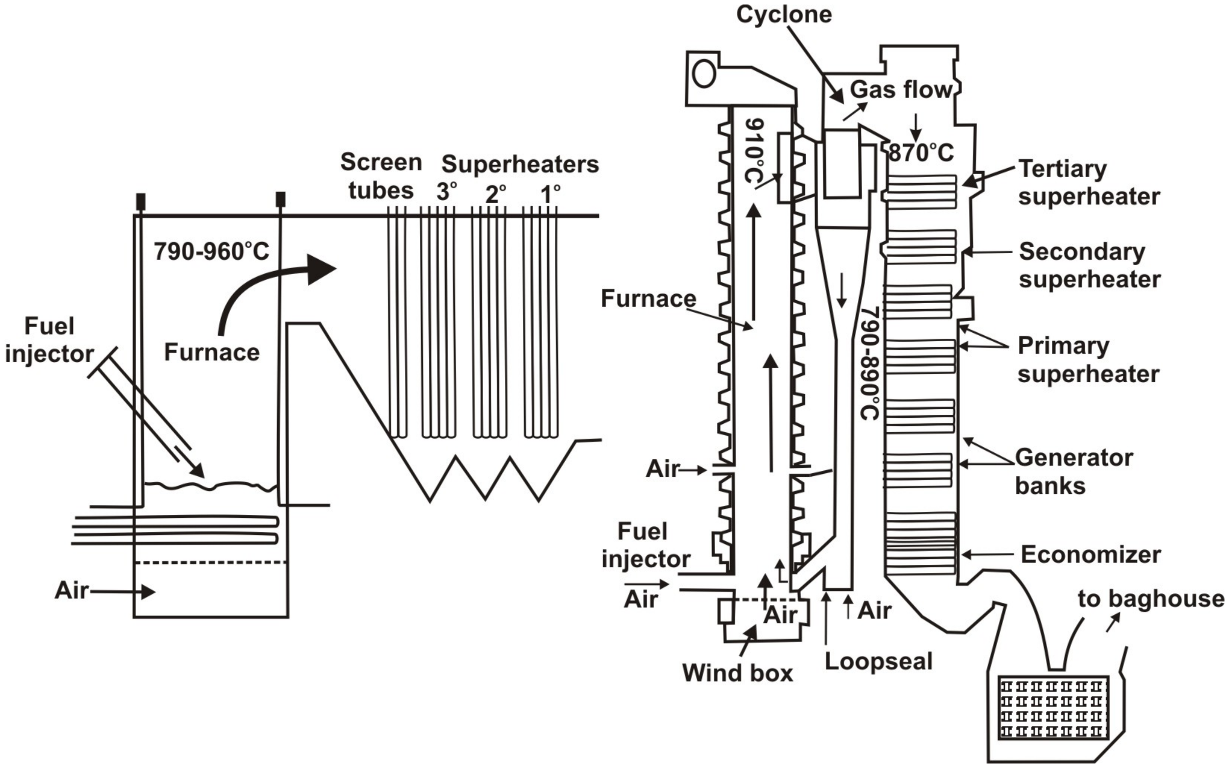

Figure 4.6: Fluid bed and circulating fluid bed combustion systems with boilers (from Miles et al. 1996)

it is a green house gas. While one cannot escape emitting it in the combustion process because the carbon present in the biomass is responsible for it, limiting its emission is possible through increased combustion and utilization efficiency. Thus reducing its use to meet the objectives of an intended industrial operation or domestic use will help mitigate its emission.

The emissions of CO and NO_x have contradictory trends. CO is emitted due to lack of oxygen in the combustion zone having CO. It is essentially a product of fuel-rich condition. This is also evident in Table 4.6. NO_x represents a mix of NO and NO_2, though largely composed of NO ($\sim$ 90 %). Its production is high at high temperatures and when oxygen is present. It is a serious emission problem with fossil fuels that are designed to burn optimally to achieve high temperatures in combustion devices. Its emission in the fuel rich condition is very small. Thus, limiting CO demands that excess air fraction be provided; this has penalties on thermal efficiency. Also it encourages NO_x production. While there are several routes to limit its emission [see for instance, Mukunda, 2009], one of the simplest techniques called rich-quench-lean involves initially burning under rich conditions, then mixing with air at high temperatures for oxidation to be completed and taking off the product gases at limited residence times beyond this stage so that the oxides of nitrogen do not have sufficient time to form. Fortunately it does not pose a serious problem in the case of biomass because at the peak temperatures achieved (<1300°C, more close to 1000°C), its production is not significant. There are exceptions that arise in dealing with treated wood or old wood (Alte-holz as it is termed in Germany) that comes about when houses are demolished. These contain chemicals used as preservatives and have some times larger fraction of fuel bound nitrogen. In these cases, fuel rich combustion generates a fair amount of ammonia.

Sulphur dioxide emissions are not significant in biomass combustion since sulphur is nearly

Table 4.11: Data on large biomass combustion plants, F-to-E = Fuel to electricity, AgW = Agricultural wastes, BFB = Bubbling fluid bed, Mab* = Måbjergværket, Denmark, 1993, VibG = Vibrating grate, cigar burning type, mix = straw, 16 % + wood, 40 %,MSW, 23 %, nat. gas rest

Plant	Power MWe	Boiler type	Fuel used	Steam °C, atm, t/h	Eff, % F-to-E	NO_x g/MJ	CO g/MJ	PM mg/MJ
McNeil	50	TrG	Wood	510, 92, 221	30	0.074	0.177	4
Delano	27	BFB	AgW	513, 93, 115	29	0.025	0.065	-
Mab*	34	VibG	mix	538, 70, 158	30	0.108	0.130	4

absent except for a few biomass and hence poses no serious issue.

Industrial plants and devices have specifications on the emissions of CO, NO_x, SO_2 and have specific devices to deal with them. If CO is in excess, a catalytic converter is used to oxidise it. For limiting NO_x emissions one of the several techniques needs to be adopted. Particulate emissions also have to be limited. Cyclones and bag filters are used to limit their emissions. All these require many active devices that need significant electrical energy.

Biomass is also used in domestic cooking applications. It is here that the challenge of ensuring high performance with minimum emissions is to be taken up as otherwise the indoor air quality will be affected. Much work on domestic stoves done over last five decades has depended on free-convection for the supply of air to the combustion zone invoking the lack of electricity in the rural domestic environment over the world. Changing world scene has made available electricity at least several hours a day in more places than what it was ten years ago and this allows the possibility of using fans at power level of watts to provide good thermal output of several kW. But even to achieve these goals principles of combustion outlined in this chapter and those that can be read in books on combustion (see books identified in ref. 3 at the end of this chapter) are needed. The principles of obtaining good combustion by two-stage combustion in such devices are outlined in chapter 8.

4.15 Performance of large combustion systems

Several large combustion systems have been built in the USA and Europe. The data drawn from Boerk et al (1995) is summarized in Table 4.11. The overall efficiencies of these plants that use very high pressure boilers with superheat seem to achieve efficiencies of about 30 %. The McNeil system at Vermont in the USA uses as-received chipped biomass at 45 to 50 % moisture. If the biomass were dried with exhaust heat or other strategies, the efficiency would perhaps go up by a few percent. The emissions to the atmosphere are small indeed and obey the national norms.

4.16 Summary

This chapter has dealt with the principles of combustion with special emphasis on biomass. The properties of combustion that apply to fossil fuels apply in the same way to biomass as well. However, the fact that biomass has varying intrinsic composition with ash varying up to 20 % along with varying amounts of moisture adds dimensions that need to be taken care. Clearly, moisture reduces the peak adiabatic flame temperature and it is important to avoid the degradation in performance by using drying procedures using low grade heat before the biomass is used in furnaces meant to deliver performance. And the presence of ash in biomass needs to be accounted for in the design. One of the additional issues that impinges on the design of biomass based combustion systems is that the same combustion system must be able to handle a wide range of biomass particularly when it arises from agriculture as its availability is seasonal and could vary over years because of changing crop pattern.

The stoichiometric air:biomass (mass) ratio of most dry biomass ranges between 5 and 6 whereas with hydrocarbons (fossil) it is 15 to 17. This recognition (that biomass based fuels need about a third of the air for liquid hydrocarbons) is not to be lost-sight-of in the changes one effects to burn solid fuels instead of liquid hydrocarbon fuels or more usually coal in the same combustion environment. The relationship between the elemental composition of biomass and stoichimetric ratio is important for proper design of furnaces. Limiting excess air ratio is one way to ensure achieving as high a temperature as possible.

The procedure to determine the equilibrium composition at any fixed high temperature requires that element conservation equations and equilibrium relations for an independent minimum set be solved together. Even for many simple systems, the size of the problem is not small and it is not easy to compute the composition by simple means. This is usually done by minimizing Gibb's free energy or Helmholtz free energy in computer based software with suitable algorithms. The software has been available over the last three decades for open access and has been used extensively. Typically, given a set of reactants and operating conditions, it takes only a second or so in modern day computers to get to the solution.

Biomass is a less energetic fuel compared to liquid hydrocarbons (kerosene, gasoline and diesel). Its calorific value is about 40% of that of liquid hydrocarbons. If ones wishes to change a furnace from liquid hydrocarbon fuel to biomass based operation, one needs to use at least 2.5 times the amount of liquid hydrocarbon. However because of efficiency considerations, the factor is closer to 2.5 to 3.5. Rather curiously, it may turn out that when clients in semi-industrial installations using fossil fuel burners (badly designed or/and operated) find that a well designed biomass combustion device works with this factor of 1.5 making it far more economical.

Large scale combustion systems use travelling grate, include grate systems with stage combustion that enables reduced emissions. Using agricultural residues with higher fractions of potassium and sodium can lead to many operational problems that can be addressed only partially through fixes described earlier. A true way of resolving the problems is to adopt modern gasification technologies, for these allow for the removal of the problem creating compounds along the conversion pathway so that the gas that is likely to be finally made available will not have the alkali related problems.

Designing combustion systems for high combustion efficiency and low emissions (actually concomitant) need the understanding of mixing and chemical reaction that are parts of a combustion process discussed in this chapter and also found in more advanced books on combustion.

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5 Biomethanation or Anaerobic digestion

5.1 Introduction

Biomethanation is a process of converting the carbon (and hydrogen) present in biomass using bacteria into gases, namely, methane (CH_4) and carbon dioxide (CO_2); these gases can be used for generating high grade heat or electricity. Biomethanation can also be called *bacterial bio-gasification (anaerobic)* as different from thermal bio-gasification or simply biomass gasification as is usually understood. Different from anaerobic process, there is an aerobic process that is the basis of composting; here the set of bacteria that flourish in the presence of oxygen will convert carbon to carbon dioxide. This process does not yield energy for use. In view of the possibility of replacing fossil fuel based energy by waste generated energy to whatever extent possible makes the biomethanation process far more interesting and valuable.

In this chapter we will be concerned with anaerobic digestion of wastes. Wastes in the present context imply parts of biomass remaining after human and animal (domestic) consumption as well as select industrial and agricultural wastes. Sometimes, food itself becomes a waste; also meat being a food for human beings, wastes of animals used for meat production constitute another feedstock.

What is used for human consumption consists of only five substances: carbohydrate, protein, fat, vitamin, and mineral. Animal consumption will consist of cellulose and other animal meat that is made up of these five substances. Carbohydrates are sugars, starches, (and dextrin, and gums). One of the important terms that refers to sugars and starches is *saccharide*. There are two types of saccharides – *mono-saccharides* which are also called the simple sugars, and *poly-saccharides* which are also called the complex sugars. Complex sugars are broken down in the human body by digestive process into simple sugars. This happens by taking apart the molecules at the water links in the structure by a process described as hydrolysis (break-down of water). The simple sugars in foods are a variety: sucrose, fructose, lactose, and maltose though finally the body breaks down these into the well known sugar molecule - glucose through the same process of hydrolysis. Sucrose is table sugar obtained from sugarcane and sugar beets. It is also naturally present in some amount in most fruits and vegetables along with higher amounts of other sugars. Two other names for sucrose are dextrose and saccharose. Fructose is the form of sugar found in fruits, honey, and corn. Fructose is refined to make corn syrup. Lactose is the sugar found in milk and cheese. Maltose is the sugar in grains. And, all four of the sugars break down easily into glucose in two simple, water-related steps. Starches include such foods as potatoes, cereals, wheat, rice and other grains. Starches are complex sugars, and complex sugars break down into one of the simple sugars (maltose), and then to glucose by again, hydrolysis. Starches are often given names that end in the letters "-an," such as glycan or mannan.

Cellulose is built up of a large number of glucose molecules. The main difference between starch and cellulose is that while all the repeat units of glucose present in starch are unidirectional, each successive repeat unit of glucose present in cellulose rotates at 180° around the axis

Table 5.1: Composition of some food wastes, TS = total solids, Moisture = 100 - TS, %, VS = Volatile solid fraction of total solids, Ash = 100 - VS, %, (from Boualiagui et al, 2005 and other internet sources)

Item	TS %	VS %	Cellulose %	Lignin %
Food waste	27	96	12 - 16	4 - 6
Fruit + Veg mix	10	90	15 - 18	4 - 6
Pinapple peel	12	95	47	7 - 9
Apple peel	15	97	44	4 - 6
Coffee pulp	68	88	40	7 - 9
Topioca	87	97	-	-
Pressmud	24	77	29	6 - 10

of a backbone made of chains of polymers, relative to the last repeat unit of cellulose. Another way of expressing this is that the units of glucose in starch are connected by what are known as α linkages, while the units of glucose in cellulose are connected by β linkages. This difference makes starch edible while not so with cellulose.

Proteins are distinguished from carbohydrates in that their structure that involves polymers of amino-acids characterized by the presence of an amine group (-NH_2), a carboxy group (-COOH) and a hydrogen atom (-H) with twenty of them with different side chains with hydrocarbon radicals. The presence of NH_2 groups leads to the formation of Ammonia (NH_3) during the biomethanation process.

Plant growth processes will arrange themselves such that the fruits contain sugars and starch and in some cases proteins within the core but usually deposit on the outer layer (peel) far more of lignin to discourage bacteria from attacking the inner part. Even so, the lignin in the peels is about 4 to 10 % in most cases in contrast to lignin in wood - about 25 %. One of the principal features of bacterial conversion processes is that bacteria work on sugars, starch, hemi-cellulose, and cellulose in a decreasing order of rate, simply because of greater structural content of the latter compounds. Bacteria converts lignin very little. Further, the conversion processes of these components when the substrate is a mix of these, as is usual, is dependent on the internal structure of the way these components are arranged. A rule of thumb used is that about two to three molecules of cellulose around each molecule of lignin remain unconverted. Biomass with larger lignin content qualifies *the least* for anaerobic treatment. The cellulose and lignin contents of some fruit and food wastes are presented in Table 5.1. The fact that Lignin fraction is small in these substances and their dry solid content is small qualifies them for biomethanation. If the material throughput is not large the thin peels can get air dried in the open air and such matter can qualify for thermochemical conversion as well (discussed in the next chapter). Table 5.2 provides the details of the conversion process of three different kinds of biomass [Donald Klass, 1998]. It is clear that lignin is converted the least; cellulose, hemicellulose and crude-protein are converted to varying magnitudes. Thus the organic content of most biomass gets converted by about 70 to 73 %.

5.2 Conversion process

Biomethanation follows a four-step reaction pathway as described in the section on biomethanation in Chapter 3 also shown explicitly in Figure 5.1.

The reaction pathways to acetate (CH_3COOH) are described as below. These are a smaller

Table 5.2: Comparison of anaerobic conversion of components of biomass in different plant wastes (Klass, 1998)

Component	Coastal Bermuda grass	Gaint brown kelp	Biomass waste-blend
	% VS / %converted	% VS / %converted	% VS / %converted
Cellulose	31.7 / 65	8.9/8	44.6/32
Hemi-cellulose	40.2 / 67		37.8/86
Crude protein	12.3 /	29.3/ 8	12.0/24
Lignin	4.1 / 9		5.5 / 0
Mannitol		34.5 / 71	
Algin		26.2 / 85	

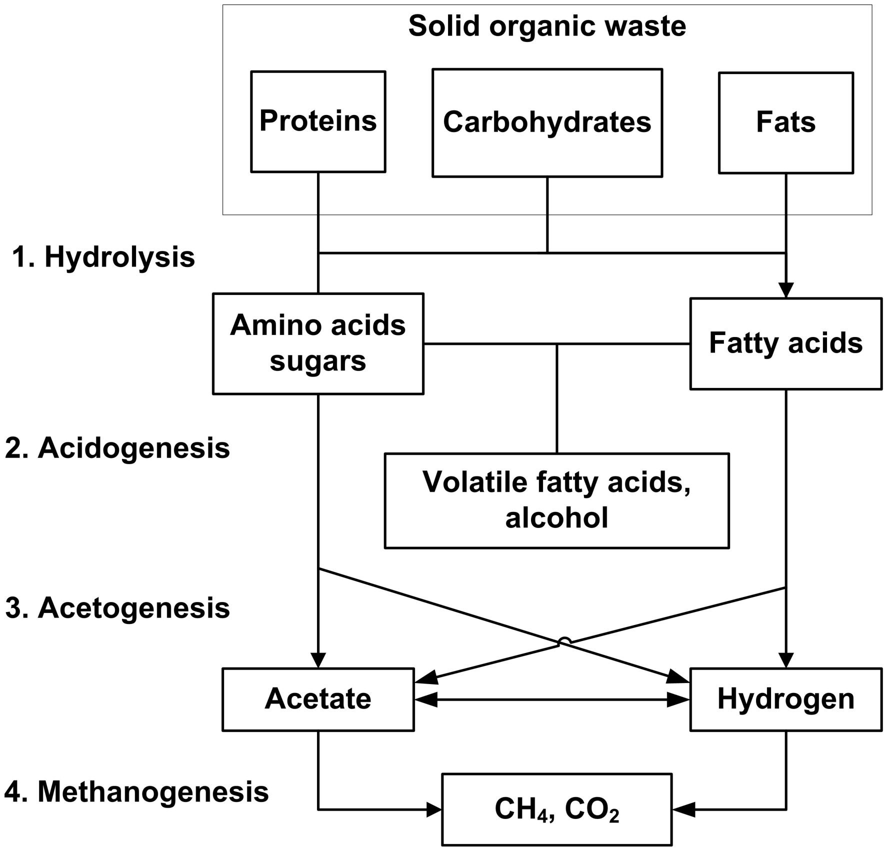


Figure 5.1: The pathways from organic waste to biogas

set than is suggested in Klass (1998).

Acetogenic reactions

$$CH_3CH_2COOH \text{ (Propionate)} + 2\ H_2O \rightarrow CH_3COOH + CO_2 + 3H_2 \quad -76.1\text{ kJ}$$
$$CH_3CH_2CH_2COOH \text{ (Butyrate)} + 2\ H_2O \rightarrow 2CH_3COOH + 2H_2 \quad +48.1\text{ kJ}$$
$$CH_3CH_2OH \text{ (Ethanol)} + H_2O \rightarrow CH_3COOH + 2H_2 \quad +9.6\text{ kJ}$$
$$CH_3CHOHCOOH \text{ (Lactate)} + 2\ H_2O \rightarrow CH_3COOH + CO_2 + H_2O + 2H_2 \quad -4.2\text{ kJ}$$

Methanogenic reactions

$$CH_3COOH \text{ (Acetate)} + H_2O \rightarrow CH_4 + CO_2 + H_2O \quad -\ 31.0\text{ kJ}$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad -135.6\text{ kJ}$$

Synthrophic reactions

$$2CH_3CH_2CH_2COOH + 4\ H_2O \rightarrow 4CH_3COOH + 4\ H_2 \quad +96.2\text{ kJ}$$
$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad -135.6\text{ kJ}$$

The values of energy indicated towards the right are the free energy of the reactions [Parawira, 2004]. The net free energy of the reaction set is − 39.4 kJ. While in a well balanced system, the magnitude of intermediates will be small, the process may tend to instability if the more energy yielding and non-energy limiting hydrogen pathway leads to higher amounts of hydrogen. This leads to the accumulation of acids (called volatile fatty acids - VFA) with accompanying decrease of pH affecting the population of methanogenic bacteria seriously. The acetogenic bacteria are very slow to grow; also, they are sensitive to fluctuations in organic loads, and to environmental changes. Their growth rate depends on low fraction of hydrogen for the acetogenic degradation to proceed. The “syntrophic” associations with hydrogen-consuming methanogens are required (McCarthy, 1982). For clarity, syntrophy means “eating together” and refers to the interdependence of the hydrogen-producing and hydrogen-consuming methanogenic bacteria. Such cooperative associations between acetogenic and/or acidogenic bacteria as well as methanogens are necessary when such reactions are thermodynamically unfavourable, as indicated by the conversion of simple substrate intermediates to acetate and hydrogen and their use to produce methane.

In addition to energy considerations, one needs to determine the rates of reaction. While the constants in the reaction rates are too many for description and accurate determination, a simple measure would be to determine the rate of acito-genesis and the rate of methano-genesis from the acetate. Measured rate constants for glucose and cellulose for acetate generation and for the conversion of the acetate to methane show inverse time constants as 3.5 hours for glucose, 14 hours for cellulose and 48 hours for the acetate [Klass, 1998]. These data confirm the broad features described above. The hydrolysis, acidogenesis and acetogenesis can be treated as one unit and methanation as another unit. This is because, the first three processes can be conducted at pH levels between 5 and 6.5 where as the methanation step is carried out at pH levels close to neutral state (7 ± 0.3). Reactor designs that combine the units 1 and 2 are single-step reactors and those that separate the two are two-step reactors. There are claims that if the process is conducted with due diligence, even a single stage reactor can perform as well as two-stage reactor. Process stability is usually better with two-stage system particularly when we account for non-compliance in operational procedure as it often happens.

It has been well known that the conversion process is affected by temperature, C:N ratio of the feedstock, nature of the culture used as inoculum, and the presence of some elements that

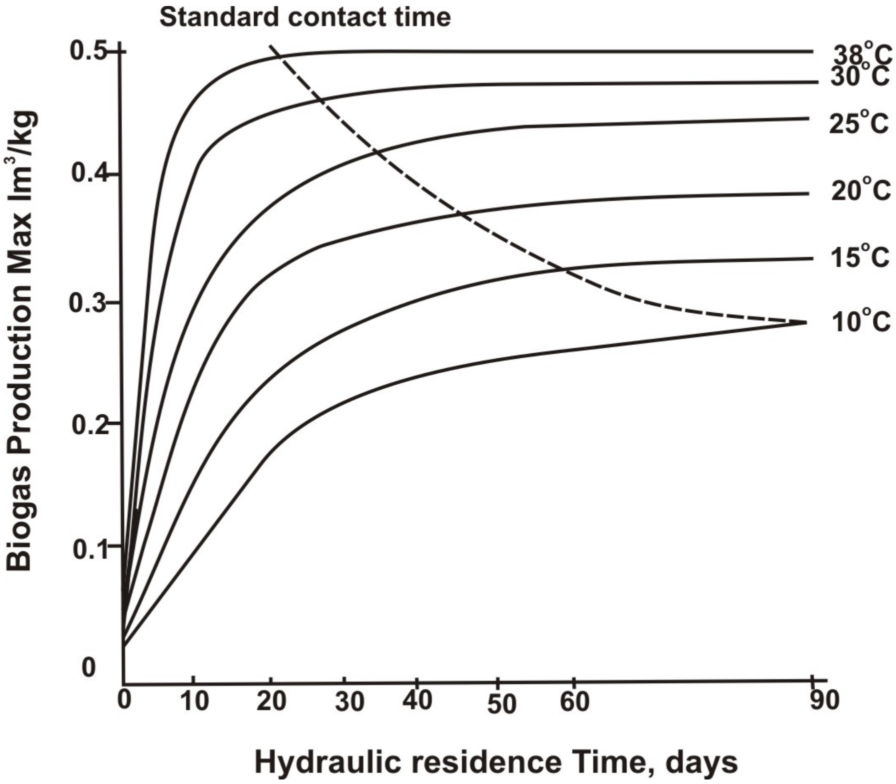


Figure 5.2: Gas output (m^3/kg VS) as a function of hydraulic residence time (days) and liquid temperature

would be beneficial up to a certain fraction beyond which they will be toxic. Temperature should be optimally at 55°C for thermophillic bacteria to operate and 37°C for mesophillic bacteria to operate. While operations at higher temperature will improve the biochemical reactivity and hence the conversion rate, the operation is known to be sensitive to temperature fluctuations. It is used sparingly generally when the in-feed itself is at high temperatures as it happens in distillery effluents. In fact the in-feed will be at temperatures close to 70°C and needs to be cooled before being allowed into the reactor. Most other situations where the infeed is at ambient temperature, it will need to be heated to desirable operational temperatures. In such situations, reactor temperature of 37°C (suitable for mesophyllic bacteria) is chosen for operation; this will ensure higher operational stability. If the temperature drops from this value the conversion drops. The results of the gas output as a function of residence time and temperature drawn from Semmler (2004) are set out in Figure 5.2. While Semmler (2004) does not indicate the specific biomass used in the study, it is assumed to a mix of animal wastes. Even if the actual values are dependent on the actual substrate, the broad behavior would be about same as what is presented in Fig 5.2. The term VS refers to volatile solids that constitute the organic dry fraction of the feedstock [essentially, VS fraction = (1 - ash fraction)]. The data presented here are revealing. Biogas digesters are designed for residence time of 30 days when the feedstock constitutes a mix of wastes. This diagram shows that the gas produced for this residence time varies by substantial factor depending on the temperature. In order to capture this feature, the results of output for 20, 30 and 90 days of hydraulic residence time are set out in Table 5.3. The maximum output, $V_{g,f}$ is considered what is obtained at 90 days. Some substrates may continue to go through the conversion process beyond that. However, to be of value to practical applications, the residence time must be as low as possible. This will enable reducing the volume of the reactor and associated cost of construction. The table also shows the fraction of

Table 5.3: Gas output, V_g in m^3/kg VS for various hydraulic residence times

T$_{liq}$	38	30	25	20	15	10	°C
V_g (20 days)	0.48 (98)	0.44 (95)	0.40 (92)	0.32 (89)	0.22 (72)	0.16 (70)	m^3/kg VS (% max)
V_g (30 days)	0.49	0.46	0.43	0.34	0.26	0.20	m^3/kg VS
$V_{g,f}$ (90 days)	0.49	0.47	0.44	0.36	0.31	0.23	m^3/kg VS

the gas captured at 20 days residence time. *The amount drops significantly below 20°C*. The ambient temperature falls below this value in large parts of India for four to five winter months (December to April) making biomethanation proceed at very low rates. The biogas composition has 55 ± 5% CH_4 in most of these cases.

The behavior shown in Fig 5.2 can be captured in a correlation using the fact that biomethanation is a first order reaction given by $dV_g/dt = \alpha V_g$ where V_g is the gas produced per unit volatile solid and α is a rate constant. The solution can be represented by

$$V_g = V_{g,f}\left[1 - \exp(\alpha(T_{liq})t)\right] \tag{5.1}$$

where t is time in days and the constant α is a function of the liquid temperature, T_{liq} (in Kelvin) and is obtained by curve fit of the data as

$$\alpha = 3.83\left[1 - \frac{311}{T_{liq}} + 0.069\left\{[\frac{311}{T_{liq}}\right\}^4\right] \tag{5.2}$$

This curve-fit produces good results for liquid temperatures down to 15°C quite accurately. These data show that a 10 degree drop in temperature from 38°C leads to gas output reduction by 8 to 10% and a 20 degree drop in the temperature which is more likely to occur in practice (over an year in large areas in India) leads to a drop in gas generation of 45 to 50%. Further, ambient temperature biogas reactors in field conditions with all the variability in the nature and rate of feed produce about 0.25 to 0.35 m^3/kg VS. These values are only about 60% of the best yields possible. All these lead to a conclusion that maintaining temperatures close to 38°C helps in optimizing the conversion rate; this also helps in reducing the reactor volume for a desired throughput.

The optimal C:N ratio for the in-feed is about 25 since the bacteria consume carbon about 25 times as fast as they do nitrogen. Lower amount of nitrogen does not help maintain the bacterial growth. Excess amount of nitrogen also inhibits the conversion rate. Most living body elements like blood and urine are high in nitrogen and therefore have a low C:N ratio (2 to 3). Many wastes like bread crumbs, potato wastes, fruit wastes, cow dung, horse dung, sheep waste, some weeds all have C:N ratio of 25 to 40. Wood shavings, corn stalk and some straws have very high C:N ratio (60 to 200). When the C:N ratio of the in-feed departs from 25 significantly, one needs to use a mixed feed such as to bring C:N ratio close to this value.

The culture used as inoculum will affect the biomethanation process. A study was specifically conducted with this objective [Bozadzhiev et al, 2007] on distillery effluent with COD and BOD of 85 and 53 g/lit, total solids of 75 g/lit, protein of 23 g/lit, reducing sugars of 4 g/lit, nitrogen, phosphorous and sulfur of 7.2, 1.3 and 2.7 % of total solids at a pH of 3.6. Two classes of cultures drawn from (a) bottom sediments of a lake and (b) cow dung were studied. The results shown in Figure 5.3 clearly indicate significant differences between the two cultures. The lake bed microbial consortia seem to do distinctly better than cow dung culture in terms of rate and extent of biomethanation. A simple solution to this problem clearly is to use a range of inoculums so as to let the system decide which of them succeed in the process. This process will indeed take a reasonable time before things get settled. When it comes to metals

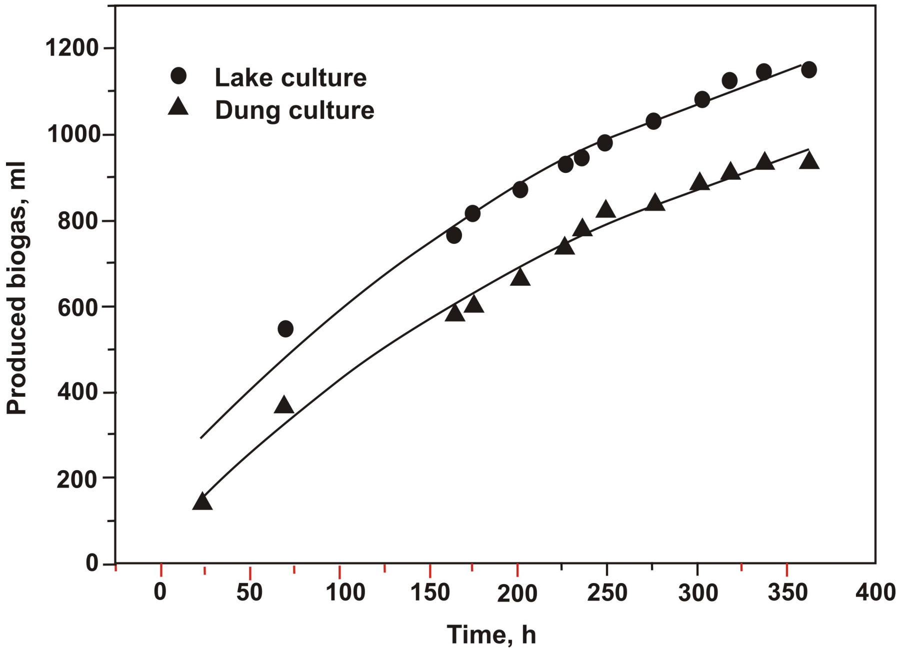


Figure 5.3: Biogas generation with time on distillery wastewater with two different inoculums

Table 5.4: Concentrations of metals (g/liter) for optimum, mild and strong inhibition

Metal	Optimum desirable	Mild inhibition	Strong inhibition
Sodium, g/lit	0.1 - 0.2	3.5 - 5.5	> 6
Potassium, g/lit	0.2 - 0.4	2.5 - 4.5	> 10
Calcium, g/lit	0.1 - 0.2	2.5 - 4.5	> 7
Magnesium, g/lit	0.08 - 0.15	1.0 - 2.0	> 3
Ammonia, g/lit	0.05 - 1.0	4.0 - 6.0	> 8
Sulfide, g/lit	up to 0.01	0.1	> 0.2
Chromium, % solids	-	2	3

and other elements there are known levels of optimum desirable concentration, moderate and strong inhibition as presented in Table 5.4. The beacterial digestion process is specially sensitive to sulfides. Obtaining enhanced performance from a given system demands that attention be paid to the micro-nutrients; also awareness of inhibition aspects is important to ensure that the plant continues to be operated well.

5.3 Characteristics of liquid industrial effluents

Liquid industrial effluents occupy an important target for biomethanation process. *This is primarily because the effluent is largely in dissolved state so concentrated as not to allow direct discharge and yet so dilute that other treatment processes can be expensive*. Biomethanation allows conversion to a gas that can be used for power generation or high grade heat. We will first examine the two quantities - Bacterial Oxygen Demand (BOD) and Chemical Oxygen Demand (COD) that are used to describe the organic content of the effluents. The oxygen required to oxidize the organic content in the liquid to gaseous products is split into two parts: one that can be dealt with by bacteria and another that can be chemically dealt with. For historical reasons, the procedure that was used to characterise the water of Thames river into which all domestic and industrial effluents were discharged was used as a standard for BOD. The ability

Table 5.5: The BOD and COD of several effluents

Effluent	BOD (g/lit)	COD (g/lit)
Sewage	0.2 - 0.5	0.4 - 0.8
Distillery	45 - 50	90 - 100
Paper industry	4 - 9	12 - 25
Dairy	1 to 10	2 - 25
Corn starch	4 - 12	10 - 20
Tannery	1 to 3	3 - 6
Abattoir	3 to 4	6 - 10

Table 5.6: The COD ratio of specific organic matter, COD* in terms of oxygen-to-organic matter (mass)

Organic matter	Formula	COD*
Carbohydrate	$(C_6H_{10}O_5)_n$	1.2
Protein	$C_5H_7NO_2$	1.64
Fat	$C_{57}H_{104}O_6$	2.9
Acetate	$C_2H_6O_2$	1.3

of the bacteria to oxidize readily available organic matter during a five-day incubation period at 20°C is determined by estimating the dissolved oxygen at the initial stage as well as at the end of five days. This difference shows the amount of dissolved oxygen that was used to oxidise the organic matter by the bacteria. In contrast, COD method uses a strong chemical like potassium dichromate to oxidize organic matter in the liquid by keeping the mixture for about two hours and estimating the amount of dichromate consumed in this time. Even though COD and BOD are two different measures not related to each other in general, correlations have been developed for specific effluents through experimentation. Typically, COD = α BOD with α = 1.5 to 2.

Typical characteristics of several effluents are listed in Table 5.5.

If one wishes to connect the COD with the magnitude of the organic matter in the effluent, one needs to make stoichiometric calculations of the oxidation of the organic matter. For specific organic matter, Table 5.6 shows the results for carbohydrates, proteins, fat and acetate.

Thus, if the measured COD is say, 100 g/liter, the organic content will be about 30 to 50 g/liter. Typical characteristics of the effluent from a distillery (spent-wash) from two different plants are shown in Table 5.7. One can notice that the effluent has a large fraction of dissolved organics with potassium based compounds the largest fraction. A typical distribution of various components in a dairy plant is presented in Table 5.8. As can be noted, the parameters vary very significantly over the various sections. The important point to note is that the volatile solids form a small fraction.

5.4 Liquid biomethanation reactors

Given the possibility that a range of micro-organisms needed in the conversion process has been introduced into a reactor, the key parameter that controls the design and operation of a biomethanation reactor is the residence time. An important point about these liquid biomethanation reactors is that the composition of the influent consists largely of acids of various kinds. For instance, Winery distillery effluent has a composition: tartaric acid (27 %), lactic acid (29 %), succinic acid (26 %), acetic acid (10 %), and malic acid (8 %) [Wolmarans and de Villiers,

Table 5.7: Various characteristics of distillery spentwash

Parameter	Batch process	Continuous process
Volume (lit/lit alcohol)	14 - 15	10 - 12
pH	3.7 - 4.5	4.0 - 4.3
COD, g/lit	80 - 100	110 - 130
BOD, g/lit	45 - 50	55 - 65
Total solids, g/lit	90 - 110	130 - 160
Total volatiles, g/lit	60 - 70	90 - 110
Inorganics dissolved, g/lit	30 - 40	35 - 50
Chlorides, g/lit	5 - 6	6 - 7.5
Sulphates, g/lit	4 - 8	4.5 - 8.5
Total nitrogen, g/lit	1 - 1.2	1 - 1.4
Potassium, g/lit	8 - 12	10 - 14
Sodium, g/lit	0.4 - 0.6	1.4 - 1.5
Phosphorous, g/lit	0.2 - 0.3	0.3 - 0.5
Calcium, g/lit	2 - 3.5	4.5 - 6.0

Table 5.8: Composition of waste waters obtained in various sections of a dairy plant, all except pH in g/lit (Dairy-data, 2010)

Constituents	Cheese plant	Milk receiving station	Casein plant	Butter, oil Ghee section	Pooled dairy effluent
pH	6.7	8.2	7.7	7.1	6.1
Total solids	2.25	3.62	0.65	3.4	1.65
Suspended solids	0.6	1.3	0.1	2.2	0.65
Volatile solids	0.025	0.075	0.055	0.065	0.06
Oil and grease	0.52	0.69	-	1.3	0.29
Chloridea	0.1	0.095	0.07	0.1	0.115
Phosphates	0.012	0.010	0.005	0.002	0.010
Calcium carbonate	0.48	0.4	0.46	0.42	0.53
COD	3.13	2.60	0.37	3.2	1.34
BOD	2.15	1.62	0.2	1.25	0.81

2002]. Dairy effluents have a larger fraction of suspended solids as can be seen from Table 5.8 and not much of dissolved organics, largely because milk itself is composed of 85 % water, with proteins, fat, lactose 12 % with rest mineral matter. This is true of wastes from other food processing units as well. In these cases, the reactor can make do without needing to fulfil two other functions - hydrolysis and acido-genesis that other reactors are required to do. This implies that the residence time required for conversion could be lower depending on the kind of complex acids that need to be treated.

In a continuously operating reactor, increasing the average concentration of the reactants - acids in the present case, increases the conversion rate as the reaction rate is proportional to the concentration of the reactants. However, in a biochemical system of the kind considered here, excess acids lead to imbalance in the pH of the reactor and the population of methanogenic bacteria that flourish in near-neutral pH will decay reducing the net conversion rate. Thus as the organic loading rate (OLR - the influent flow rate per unit digester volume) increases, the conversion rate is maintained till a point of time (with gas generation rate increasing with the OLR) beyond which it will begin decreasing. Typical results drawn from the work of Blonskaja and Vaalu (2006) are shown in Figure 5.4. As the OLR increases, the conversion remains nearly same up to some OLR (in this case, up to 12 g/l-day) and decreases beyond that value. Figure 5.5 shows the three types of such reactors. The anaerobic filter (Left part of the figure) uses some media inside a cylindrical reactor to enable microbial mass to attach itself and work on the organic matter that flows by. This design is most suitable for waste waters with dissolved

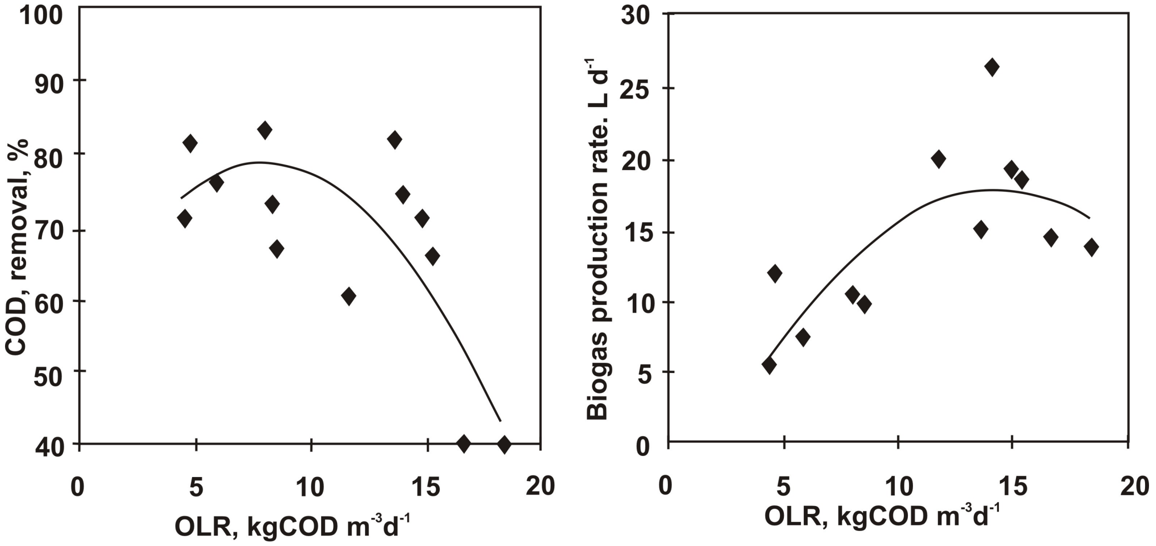


Figure 5.4: Performance of high rate biomethanation reactors

solids and little suspended solids. The standard Upflow Anaerobic Sludge Blanket (UASB) reactor (shown in the middle part) eliminates the need for extraneous material for the bacteria to stick to. Instead, conditions are created for the formation of porous granules and nodules of active bacterial matter of 0.5 to 2 mm size over a considerable zone inside the reactor. This can be used for waste-waters that include suspended solids. The granular microbial mass that gets accumulated has a sedimentation velocity of 5 to 15 m/hr and the flow velocity is kept comparable to this to ensure that the material remains suspended in the fluid. In some instances, the size of the granules could be as high as 4 mm and sedimentation velocity as high as 80 m/hr. These aspects allow higher velocities of the upflowing stream and hence reduced reactor footprint. The high velocities also help greater mass transfer between the liquid and the solids. While this design appears more elegant and has a wider applicability, washing-off of the microbial mass due to inadvertent higher speed flow past them is a point of concern; growing the bacterial mass also takes time, typically a few months in the case of large reactors. Nevertheless, UASB reactors have become very popular over the last three decades with more than a thousand large reactors currently in operation all over the world. The development is credited to Prof. Lettinga of Wageningen university in the Netherlands [Lettinga et al 1980] who having been inspired by Prof. McCarty's work [McCarty, 1964] in the USA was experimenting initially with anaerobic filters observed that a large proportion of bacterial mass had developed as granular aggregates even outside of the support material. In this period, he had visited South Africa where he saw a plant for treating wine residues in which compact granules were growing even without support material. This inspired him to develop a digester that did not need any support material. The crucial aspects of this design are (a) the choice of bacterial microorganisms that aggregate into granules and (b) an arrangement for three-phase separation - gas, liquid and solids such as to retain the solids while allowing the gas and the liquid to be drawn out separately. Inflowing stream is typically equalized, neutralized and partially acidified in a separate tank ahead of the reactor. The incoming flow is sometimes mixed with effluent recycle and then distributed into the lower part of the reactor below the sludge bed.

Further development of UASB reactor (shown on the right of Fig. 5.5) is called Expanded Granular Sludge Blanket (EGSB) that employs higher velocities in the bottom section allowing the bed to expand as it happens in a fluid bed reactor, but the geometry is enlarged towards the top to reduce the fluid velocity and so the possibility of washout. Other features of gas-liquid-solid

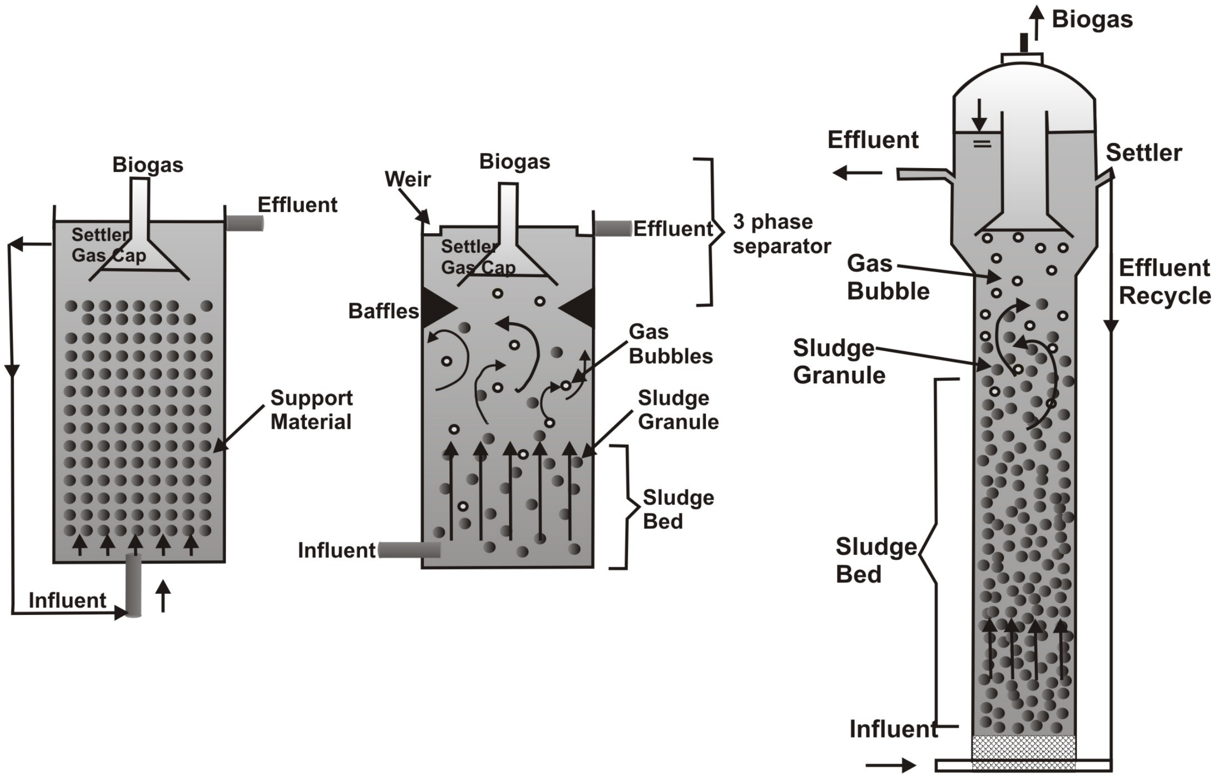


Figure 5.5: Configurations for high rate biomethanation reactors; left: Anaerobic filter, middle: Upflow Anaerobic Sludge Blanket (UASB), right: Expanded Granular Sludge Blanket (EGSB)

separation are maintained as in the case of UASB. While UASB reactors are built at 4 to 5 m height, EGSB reactors are designed at 12 to 16 m height. This is particularly recommended for low strength soluble waste waters or waste waters with poorly degradable suspended particles. Higher stream speeds provide enhanced mass transfer and reactivity.

A later development called internal circulation UASB (Driessen et al, 1999; Grant et al, 2002; Mutombo, 2004) has allowed enhanced performance in terms of accepting larger organic loading rates at high BOD/COD reduction with smaller foot print of the reactor. Figure 5.6 shows the principles and the schematic of UASB-IC reactor. The reactor is about 3 to 4 times the height of a standard UASB reactor and twice that of EGSB. The reactor is designed around large height-to-diameter ratio to reduce the foot print. There are two parts of the reactor. The bottom section that is more highly loaded and the top section that is lightly loaded. As can be noted from the right side of Fig. 5.6, the influent is pumped into the reactor through a distribution system at the bottom zone where both the influent and recycled sludge/effluent get mixed. The bottom section of the reactor compartment contains an EGSB, where most of the COD is converted to biogas. The biogas produced in this compartment is collected by the lower level three-phase separator; a significant part of the gas is allowed to move through a smaller conduit. This buoyant upward motion of the bubbles entrains water and sludge. This gas-lift moves the mixture to the gas-liquid separator located on top of the reactor. Here the biogas is separated from the water/sludge mixture and leaves the system. The water and sludge mixture is directed downwards to the bottom of the reactor via the concentric pipe that leads the liquid to the bottom of the reactor. This gets mixed with the influent, a feature discussed above. This then constitutes the internal circulation, a term associated with the name of this design. The effluent from the first compartment is treated in the second, low-loaded zone, where more of BOD/COD is removed. The biogas produced in the upper compartment is also collected in the

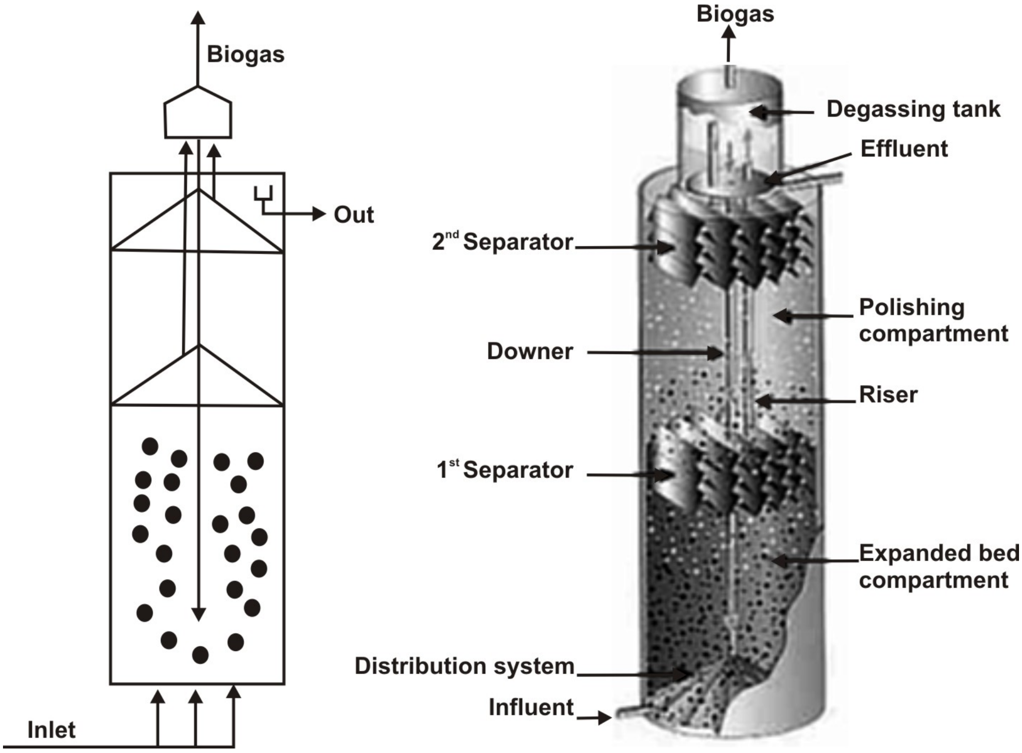


Figure 5.6: The schematic of the UASB-IC reactor. It consists of two sections with three-phase gas-liquid-solid separators in each section. The gas from the bottom separator is designed to crate a buoyant gas lift that takes the sludge to the top from where it flows to the bottom and mixes with the influent. This feature constitutes the internal circulation

top three-phase separator, while the final effluent leaves the reactor at the top region.

While UASB reactors have been designed to accept up to 15 kg COD/m^3/day, EGSB reactors provide up to 25 kg COD/m^3/day and UASB-IC reactors show good performance even up to 30 kg COD/m^3/day. Also, the COD removal goes up to 80% in the case of UASB-IC systems. The largest number of installations of these reactors is in the beverage as well as paper and pulp industries.

5.5 Performance of systems

The performance of several food industry waste reactors is presented in Table 5.9 drawn from the work of Blonskaja and Vaalu (2006). This table covers a variety of bio-reactors - Anaerobic filter (AF), Upflow anaerobic sludge blanket (UASB), Fluid bed (FB) and hybrid. Fluid bed reactors use some plastic media to create the expanded fluid bed. Hybrid systems use some combination - UASB in the bottom section and anaerobic filter in the top section.

The data shows that increased COD removal demands more reaction time. Increased OLR will limit the COD removed (CODR) for the same level of residence time. Figure 5.7 shows the % COD removed (%CODR) as a function of organic loading rate (OLR) for three different substrates. The difference in behavior is indicative of the complexity of microbial conversion process. It is particularly clear that distillery effluents are indeed very complex compared to Whey as the %CODR drops off strongly with OLR in the case of distillery effluent. A simple model for the conversion can be obtained from assuming a first order reaction rate: $dX_r/dt =$

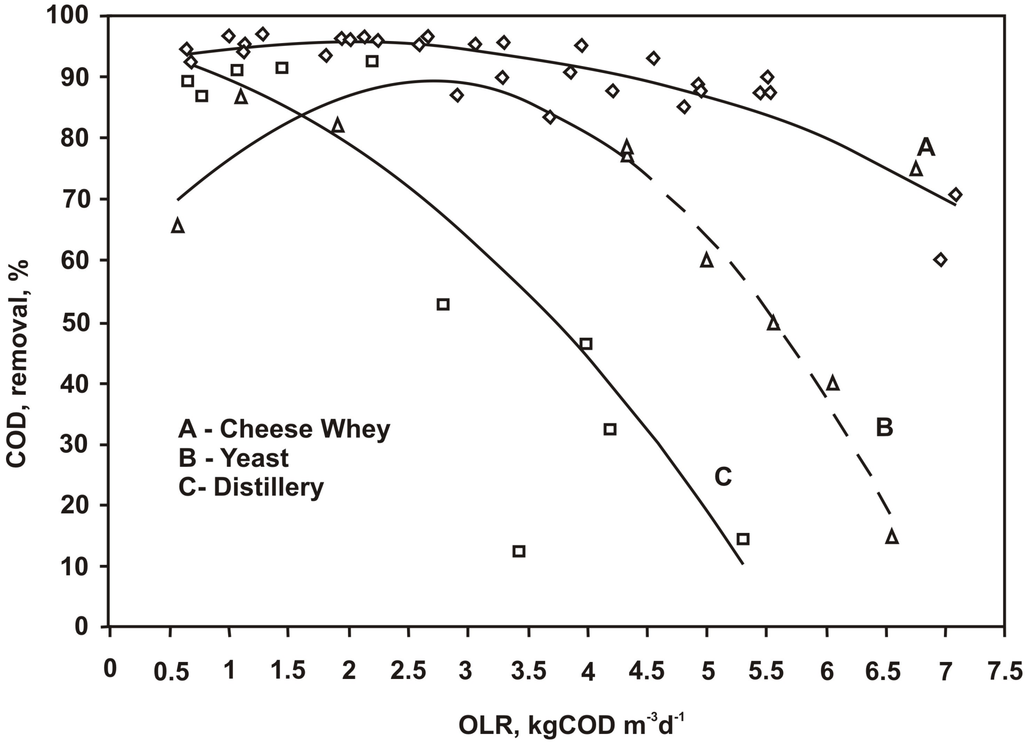


Figure 5.7: Variation of % COD removed as a function OLR for Whey, Yeast and Distillery effluent

$-kX_r$ with X_r as the mole fraction of the reactant with k, the rate constant acquiring the role of a inverse of characteristic time. The solution will be $X_r = X_{r0}exp(-kt)$ where X_{r0} is the entry mole fraction of the reactant. If the residence time is t_{res}, then $X_{rf} = X_{r0}exp(-kt_{res})$ where X_{rf} is the final mole fraction. In a flowing system, the residence time scales with distance, d and inverse of velocity, V ($t_{res} \sim d/U$). The constant k is taken as proportional to (OLR/COD), the inverse time scale of the process. The quantity 100(1- $X_{rf}/X_{r)}$) constitutes the estimate of the %CODR can therefore be expressed as

$$(1 - \%CODR/100) = \exp(-k_{sus}\frac{\text{OLR}t_{res}}{\text{COD}}) \tag{5.3}$$

The quantity M = (OLR/COD) t_{res} is non-dimensional and describes the rate of biomethanation process. The constant k_{sus} is related to the substrate as evident in Fig. 5.7. This can also be expressed as $M \sim ln[1/(1 - \%\text{CODR}/100]$. Figure 5.8 presents the results of the data in Table 5.9 in terms of M with $ln[1/(1 - \%\text{CODR}/100]$. Part of the scatter in the plot is due to different substrates having different rate constants of degradation discussed above. Though there is scatter in the plot, it appears that there is a broad trend shown by this correlation. It appears that most literature on the subject deals with COD and OLR as two independent parameters. It appears from the above analysis that there is simply only one non-dimensional parameter - namely, the ratio of residence time to (OLR/COD). If predictions are required beyond the simple approach, one needs to model the multi-step biochemistry [see for instance, Lyberatos and Skiadas, 1999, Appels et al, 2008, Feng et al, 2003]. There are two large biomethanation plants in India working on spent-wash from pulp and paper mill. The performance data from these are presented in Table 5.10. The design has two reactors running alternately. The effluent from these reactors has still a large fraction of BOD and COD left and interestingly, the fuel replacement for the boilers is only about 20 %. If we note that the spent-wash has significant amount of inorganics (see Table 5.7), it appears clearly that there is a case for seeking alternate

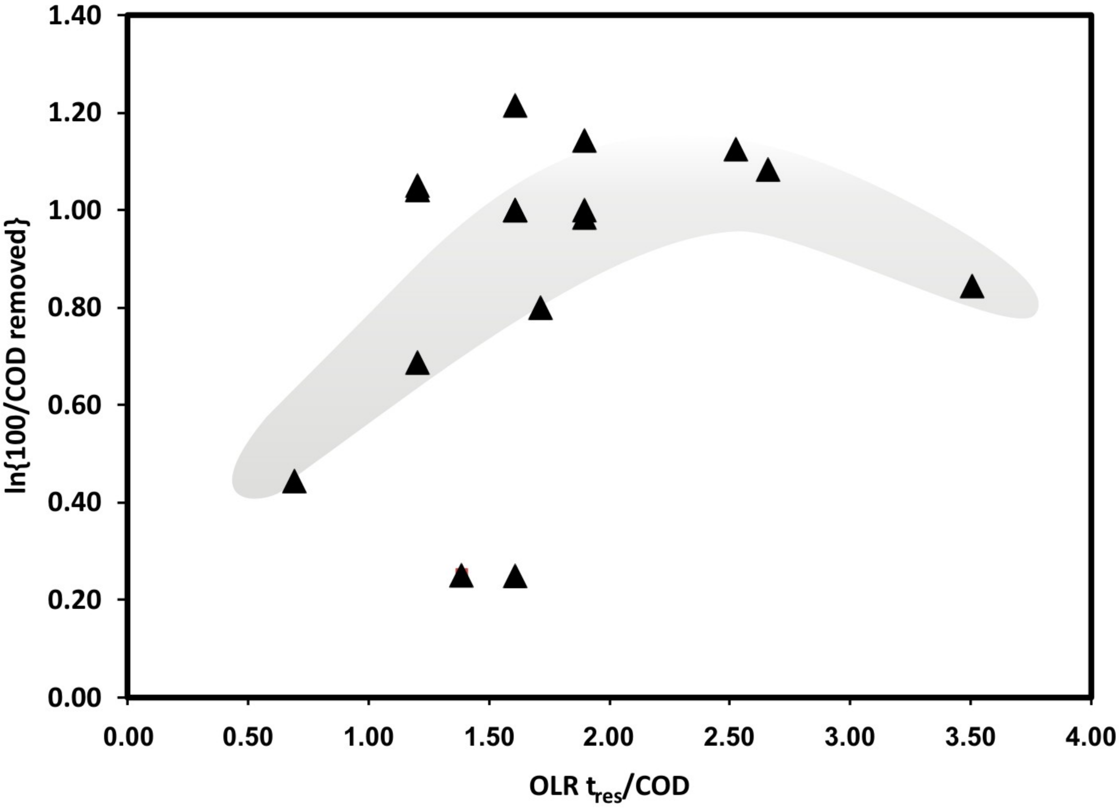


Figure 5.8: Correlation of high rate biomethanation reactors of $ln[1/(1 - \%\text{CODR}/100]$ with M = (OLR t_{res}/COD)

Table 5.9: Performance parameters of several industrial waste water treatment plants HRT = hydraulic residence time, OLR = Organic loading rate, AF = Anaerobic filter, FB = Fluid bed

Industry	Reactor Type	COD, g/lit	OLR, g/lit-day	HRT hours	COD removed %
Beer	UASB	1 - 5	1 - 15	5 - 9	75 - 80
Starch	UASB	10	15	18	90 - 95
	AF	4.5	11	10	89
	Hybrid	45	4	228	97
Potato	AF	8	8	21 - 26	80 - 93
	Hybrid	7.5	12	16	70
Dairy	UASB	3 - 33	12	65	85
	FB	28	7	24	80
	Hybrid	1.6	2	20	70
Cheese	UASB	3 - 4.5	3.5 - 15	6 - 8.2	92 - 95
	AF	40 - 70	8 - 16	96 - 120	82 - 85
	FB	3.2	22	2.4	70
	Hybrid	3.6	216	85	90
Olive oil	FB	40 - 47	-	5 - 50	87 -94
Sunflower oil	-	21	-	8 - 15	48 -62

Table 5.10: Performance of two paper mills

Item	Industry1	Industry2
Capacity, t/day	40	45-50
Raw material	Bagasse	Bagasse/Wheat straw
Pulp process	Chemical-mech	Alkaline-sulfate
effluent	Segregated black liquor	Segregated soda black liquor
pH	9 - 9.5	8.5 - 9.0
BOD, g/lit	3 - 3.5	8 - 9
COD, g/lit	9 - 10	26 - 27
Flow rate, m^3/day	2200	2000
Reactor vol, m^3	2 × 6200	2 × 2623
HRT, hours	50	24
OLR kg/m^3-day	5	12
Reactor temperature, °C	36 ± 1	36 ± 1
BOD removal, %	90	75 - 80
COD removal	70	45 - 50
Biogas output m^3/kg COD	0.45 - 0,5	-
Methane fraction, %	75	80 - 85
Boiler fuel	LSHS/biogas	Rice husk/biogas
Fuel replacement	15 %	15 - 20 %
Treated effluent BOD, g/lit	0.3 - 0.35	2 - 2.8
COD, g/lit	2.7 - 3	13 - 14

Table 5.11: The performance of the UASB sewage treatment plants established under Yamuna Action Plan, drawn from Khalil, et al, 2008

Influent temperature, °C	20 – 25
Hydraulic residence time, hours	8 – 12
Sludge retention time, days	32 – 38
Sludge bed concentration, kg TSS/m^3	65 – 70
Maximum sludge bed height, % total	85
Upflow velocity, m/hr	0.6
Volatile solid destruction, %	50
Volumetric loading rate, kg COD/m^3/day	1.2
COD removal efficiency, %	80
BOD removal efficiency, %	70

waste treatment techniques. One of those involves multi-effect evaporation to concentrate the effluent and burning the concentrated effluent as a boiler fuel and extracting the inorganic matter after it has melted. A number of biomethanation plants based on UASB design are established in India. The techno-economic aspects of the systems are set out in Khalil et al (2008). Their performance of the sewage treatment plants in the Yamuna action plan under which these were installed is set out in Table 5.11. The volumetric loading rate is indeed small compared to what the system can perhaps handle. However, the intended objective of the reduction in BOD and COD has been fulfilled in these plants.

5.6 Biogas generated

We examine the gas output for pure and practical mixed substrates; Table 5.12 includes the output of some pure substances namely, carbohydrates, fats and proteins whose composition was presented in Table 5.6. It must be noted that the volatile solids fraction is 100 % for pure

Table 5.12: Gas generated in the biomethanation reactors and energy derived, VSF = Volatile solid fraction, LCV = Lower calorific value, ds = dry solid

Substrate	VSF	Gas/kg VS m^3/kg VS	CH_4 %	LCV (ds) MJ/kg	Gas LCV (ref-solid) MJ/kg
Carbohydrate	1.0	0.7 - 0.8	50	17	11 - 12
Fat	1.0	1.2 - 1.4	72	37	25 - 32
Protein	1.0	0.6 - 0.7	70	17	13 - 15
Yeast	~0.93	0.5 - 0.6	65	15	9 - 11
Corn starch	~0.96	0.6 - 0.7	55	17	10 - 11

Table 5.13: Effect of reducing the size of the waste in-feed on the performance of a digester

Substrate	Sample size mm, mm, mm	Size reduction method	Reduction of digestion time, %
Potatoes + apples + carrots	20, 20, 20	Grater - thin strips	50
Meat	20, 20, 20	with Grinding machine	23
Sinflower seeds	5	with Grinding machine	45
Maple leaves	20, 20	Ground in a flour mill	59
Hay stems	10, 50	Ball mill with water	52

substrates (the first three in Table 5.12). However, in all the cases, the gas outputs will be such that the energy in the gas measured against the possible energy that can be released is lower by 30 to 40 %. This is due to bacterial and residence time considerations apart from the presence of inorganic matter in the structure of the material. The calorific value of the dry solid shown in fifth column is affected only by the ash content (1 - volatile solid fraction). The calorific value of the gas referenced to the solid is obtained as (fraction VS) × (Gas/kg VS) × (CH_4 fraction) × 30.5 the last column (the value 30.5 refers to the calorific value of CH_4).

5.7 Solid wastes

Solid wastes distinguish themselves from liquid wastes in having a solids content better than about 30%. Such wastes, if available seasonally, can be treated along with the liquid wastes discussed till now. They can be mixed ensuring the requirements of biomethanation - a suitable C:N ratio, presence of micro-nutrients and ensuring that these are not in excess. An important point to keep in mind is that if solid size is large it would take time for bacteria to bore through the mass. Experiments performed by reducing the size of the waste (Brown and Tata, 1990 and Palmowski et al, 1999 and Hartman et al, 1999) show that there is considerable gain in conversion time (up to 50 % on the average) if the material is brought down in size (see Table 5.13). Thus, size reduction to fine levels (of the order of hundred to several hundred microns) is of preparatory value and can be adopted for possible incorporation into waste-waters ready to undergo anaerobic treatment. This would help maintain or even reduce the residence time demands on the reactor.

The feedstock can be wastes of domesticated animals like cow, pig, sheep, goats and others as well as agricultural wastes apart from municipal solid wastes. Many of animal wastes are available in both farms and individual holdings. The conversion system in farms can be of industrial scale and those for domestic applications need to be designed separately. The anaerobic digestion can be conducted at ambient temperature, 37 or 55°C. These can either be a wet process or a dry process, wet process demanding a solid content of 8 to 12%, certainly less than 15% and dry process being able to accept feedstock up to 30% solids.

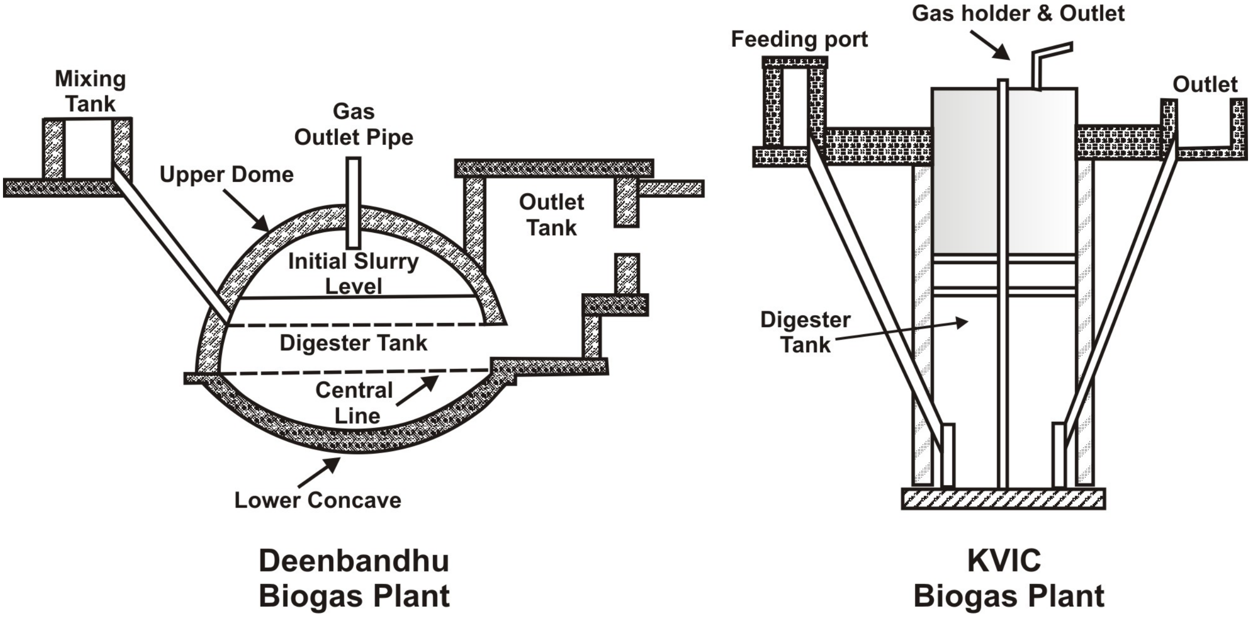


Figure 5.9: Schematic of a biogas digester with fixed dome (Deenbandhu model) and floating drum - KVIC model

The anaerobic conversion techniques combine the 4-part process described earlier into a one-step or two-step scheme. In one-step process all the four parts are combined in a single reactor. In a two-step process, the three parts - hydrolysis, acido-genesis and aceto-genesis are combined into one step and one reactor deals with this step and the methanation part alone is separated into the second step operated in a second reactor.

Thus there are several options for the conversion process. In India, biogas plants are built both for domestic needs and industrial applications. Those for domestic applications are generally single-step, ambient temperature, wet process based systems; they have been built in millions for cow dung at 2 m^3 reactor volume size (see FAO, 2010). Selected wet systems for community applications are built on cow dung at larger reactor volumes - 6 to 10 m^3. The gas generated is invariably used as cooking gas; in a few instances, power generation using dual-fuel based diesel engines or converted gas engines is also practiced.

There are several variants of biogas systems in practice in India - KVIC model, Janata model, Deenbandhu, Pragati and others. The basic difference in the design is related to the way gas is abstracted. In the KVIC model there is floating drum made of mild steel that needs to be periodically painted to extend the life. Other models have fixed structure. All the models have an inlet at one end and effluent outlet at the opposite location. The gas off-take is the top of the central dome region. Figure 5.9 shows two designs, one with a fixed dome and another with a floating metal drum. Other models are only variants of these concepts and models. The simple model outlined earlier for relating the performance of liquid biomethanation reactors is also valid in the case of one-step solid phase systems. The organic loading rate (OLR) expressed as kg COD per m^3 digester volume per day is to be be replaced by kg volatile solids per m^3 digester volume per day and chemical oxygen demand (COD) expressed as kg per m^3 of the fluid by volatile solid concentration kg per m^3 of the in-feed stream. Thus the ratio of volatile solid loading (VSL) to volatile solid concentration (VSC) replaces the ratio OLR/COD. In this case M = (VSL/VSC) t_{res}]. Thus % VS destroyed = $exp[-k_{ss}M]$, here again, with k_{ss} as the constant dependent on the substrate and bacterial population. For two-step digester similar ideas can be used to describe the process. It must be recognized that the first part of the process consists

Table 5.14: Composition of grass and cowdung

item	Grass dry, %	Cowdung dry, %
Cellulose	45	30
Hemicellulose	35	20
Lignin	10	20
Crude protein	15	5
Ash	10	25

of dilute or not-so-dilute solid phase input giving liquid phase output that needs a separate treatment. The second part involving biomethanation from volatile fatty acids and follows a mathematical description exactly like in the case of liquid reactors.

It is usually recommended that the digester be charged on a daily basis and if missed, charging on an alternate day must be ensured. Cow dung has been considered an important feedstock for biomethanation even though in many parts of India it is converted into dried cylindrical cakes or as a part of large cylindrical fuel block in front of the house. The composition of grass and cow dung composed from the work of Emmet Bennet (1936) and Znidarsic, et al (2006) is presented in Table 5.14. While grass itself does not have much lignin and ash, cow dung has far more lignin because many other components are digested in the cow's stomach; this magnitude may be the lower end of the value as the pick up of the inorganics from the soil on which the cow dung falls, as may happen in many places would be even more. Of course, in organized sectors like dairy farms, the situation is much better in terms of limited inorganic pick up beyond what comes out as dung from the cow or buffalo. When bovine dung is the feedstock as is usually the case, the recommendation is to dilute the fresh dung with equal amount of water to bring down the solids content to about 10 %. The volatile solid fraction on the basis of fresh dung is about 15 % and on the basis of diluted in-feed about 7.5 %. Thus, a 1 m^3 plant is loaded with 25 kg per day of bovine dung with 25 liters of water, the residence time amounting to 20 days with an operational temperature of 37°C. The volatile solid loaded is 3.75 kg/day. After start-up, the biogas output stabilizes at 0.8 - 1 m^3 per day with a composition of 50 % CH_4 (and 50 % CO_2). This amounts to 0.20 - 0.25 m^3/kg VS/day. The VS conversion inside the reactor will be 20 to 25 %. This is largely because of the presence of fair amount of lignin in the feedstock and a limited residence time. The gas production rate assessed in terms of volatile solids destroyed will amount to 0.9 to 1 m^3 per kg VS destroyed. If we take the calorific value of the volatile solids as 20 MJ/kg and the energy of 50 % biogas is 20 MJ/m^3, the energy conversion efficiency works out to $(100 \times (0.9 \text{ to } 1)\ m^3 / \text{kg VS} \times 20\ \text{MJ}/m^3)/20\ \text{MJ/kg} = 90 \text{ to } 100\ \%$. This is reflective of the fact that the energy conversion process has little losses as most of it occurs at low temperatures. If we note that the in-feed energy is about 13 MJ/kg total solids, the energy efficiency based on the in-feed works out to $(100 \times (0.2 - 0.25)\ m^3/\text{kg} \times 20\ \text{MJ}/m^3) / 13\ \text{MJ/kg} = 31 \text{ to } 39\ \%$. This, it can be noted is small.

Thus, while bacteria themselves are efficient, what is fed to them for conversion is not what they can deal with; to that extent they cannot help and this is why the energy conversion efficiency is low. This is not a widely appreciated feature. Of course, the argument that is made is that the effluent that comes out of the biogas reactor has a value as humus and manure. The effluent output from a biogas plant based on bovine dung has not much nutritive value since in-feed has no significant fertilizer value as measured by the nitrogen, phosphorous and potassium content called traditionally as NPK value. If the feedstock is based on fruit and kitchen wastes, the NPK value of the effluent from the digester is much better (see later). In fact, these features of energy efficiency make thermochemical conversion strategies far more competitive technically, environmentally and commercially (to be discussed later).

It is useful to estimate the size of a biogas plant for domestic applications. Typically, most houses (3 - 4 people) depending on liquefied petroleum gas (LPG) with a cooking fuel container (with 14 kg mass of LPG) consume it in about 30 to 40 days. This amounts to 0.35 - 0.5 kg/day on an average. Equivalent biogas would be 0.7 to 1 m^3/day (about the same as kg/day since methane with a lower molecular weight is balanced by carbon dioxide with much higher molecular weight). This is obtained technically from a 1 m^3 size plant. This means that in-feed of bovine dung should be about 25 kg (at 20 % moisture). This is provided by 2 cows or one buffalo. If there are other animals like sheep/goats being reared, additional wastes are available for being mixed with the in-feed. The gas output rate will be about 1 m^3 per day provided the digester is operated at 37°C. In some regions where the mean temperature does not fall below 25°C even in the winter months, the gas production rates will not fall below 0.7 m^3/day for ambient temperature biogas plants. However, in many regions, the temperature falls below this level and production rates go down. In fact, in the original plan of the Ministry of Non-conventional Energy Sources (MNES earlier and MNRE now) five zones in India were created depending on the mean temperature of winter months (Khandelwal and Mahdi, 1986). During these months where the mean temperature is around 15 to 20°C, the gas production will go down to 0.3 - 0.5 m^3/day, a magnitude that will be insufficient to meet the daily demands of cooking heat. This would imply that one needs to use 2 or 3 m^3 plants for meeting the energy demands. If only the elements required to operate the digester at optimal temperature were made, even the lower capacity plant would perhaps have been adequate.

An interesting development on biogas digesters is the use of starch as the feedstock by Karve in India (www.arti-india.org). The fact that starch is an ideal fuel for bacterial conversion with a high gas-to-in-feed ratio (0.75 m^3/kg VS, see Table 5.12) allows one to reduce the reactor size. If it is stated that one needs to build a biogas digester for obtaining 1 m^3 per day of biogas, one needs a reactor that has an in-feed of 1.33 kg of starch (for which VS = total solids) per day. If the reactor is operated at 10 % solids, one needs to dilute the starch with 13.3 liters of water. Thus the daily feed will be about 15 liters of the starch-in-water solution. The residence time needed for conversion at 37°C is between 2 to 3 days. Even if the residence time is taken as 4 days, the reactor volume should be about 60 liters. In addition, one needs a gas holder of about 0.5 m^3 capacity allowing for non-use of 12 hours. Perhaps the storage of the gas can be combined with the reactor itself. This would amount to a reactor volume of 0.6 m^3. Allowing for a near-full day storage, one deduces a reactor volume of 1 m^3. The reactor of Karve's design has a volume of 1 m^3, but operates at ambient temperature. The gas output rate will be dependent on the season and will always be lower than in a 37°C reactor. The reactor can also be fed with fruit and food wastes that are close to starch or even better and kitchen wastes that may have additional difficult-to-degrade material as well. In these cases, the output rate will depend on the substrate added. All-in-all, it is an important development that can enable commercial diffusion of the technology. This class of technologies has reached plastic water storage tank builders who supply the entire system built around plastic construction. The impact of these developments is still to occur on visible scales in India or other countries.

5.7.1 Other reactor designs and implementation

Several other researchers in India have tried to develop small size systems. A group at The Energy Research Institute (TERI) has developed a two-step digester of the UASB concept. This has not gone beyond laboratory and pilot scale studies (see www.teriin.org). The group at the centre for sustainable technologies (earlier ASTRA) has developed two alternate designs to extend the fuel to leafy biomass, a plug flow reactor and a solid state stratified bed digester (see Chanakya et al, 2004 and other papers cited therein). The aim of the first development is to deal with the leafy biomass that is light and the scum floating on water. The second design is close to dry anaerobic digester (DRANCO process - see later) and has a vertical reactor with biomass loaded from the top and the digested biomass drawn from the bottom. The liquid is continuously recycled spraying the liquid from the top. Both these designs were explored for adaptation to other feed stocks including urban solid waste. They have gained experience at laboratory level, pilot plant and field level implementations supported by funding agencies and with part private investments. Sardar Vallabhai Patel Research Institute (SPRERI), Anand, India has examined the development of vegetable waste based two-step digester and implemented in a vegetable market place. While all the systems described above are based on ambient temperature reactors, Bhabha Atomic Research Centre, Mumbai has a division that has developed a two-step digester in which the acidification is conducted under temperatures that could be near thermophilic temperatures ($> 50°$C) and the methanation at temperatures around mesophillic conditions. The first stage thermophilic operation is done in aerobic environment using solar water heating arrangement. The appropriateness of the aerobic environment has been debated (Veekan, 2005). They have set up systems at several locations. A more detailed technical analysis of the BARC system can be seen in Veeken (2005). A small number of these systems have reached the market in a non-commercial manner with the support of various agencies.

Most of these systems have been transferred for functioning to public bodies that do not have a commitment to ensure their operation and consequently, several of them have had durations of proper functioning much smaller than possible, largely unrelated to the strength of the technology (see the observations on the technologies in India by Muller, 2007). The crucial reason is that except for the approach in ARTI design that aims at using richer feed stocks (like starch and food waste) most of the others have not gone through attempt of ownership by a commercial entity. This has prevented establishing the true outreach capabilities of these technologies. There are deeper questions of whether allowing bovine dung to be used in digesters with only 50% destruction of volatile solids along with possible benefits of the slurry being used on the farms is indeed superior to the use of bovine dung in making modern fuels with high utilization efficiency. These need to be debated in coming times.

5.7.2 Conversion efficiencies

The subject of conversion efficiencies has been brought up in the earlier sections. Klass (1998) has described experiments on a variety of biomass addressing the question of energy efficiency. Fundamentally, it is related to the parameter M discussed earlier. Larger the value better the conversion efficiency. However, there are practical limits to the choice of residence time that controls the parameter M and hence the extent of conversion. Table 5.15 shows select data drawn from his work. The volatile solid converted in the reactor varies from 30 to 40 %. In large bovine dung digesters (discussed below) it goes up to 55% when the allowed residence time goes up to 30 days. It is about 40% in small digesters operating at 27 to 30°C and is about 20% in winter. The energy conversion is between 35 to 45 %. The sludge that comes out of the reactor is of course treated as manure.

Table 5.15: Conversion efficiencies of select biomass, 35°C reactor, 12 day residence time, VS loading = 1.6 kg VS/m^3 digester volume (Klass, 1998)

Item	Primary bio-solids	RDF-bio-solid blend	Biomass waste blend	Water hyacinth
Ash, %	26.5	8.4	17.2	22.7
VS (100 -ash), %	73.5	91.6	82.8	77.3
C:N ratio	10.9	22.0	26.3	20.9
VS reduction, %	41.5	36.7	33.3	29.8
Methane in biogas, %	68.5	66.0	62.0	62.8
Biogas, m^3/kg VS	0.21	0.14	0.14	0.11
Gas-to-in-feed energy, %	46.2	39.7	38.3	35.7

5.8 Large scale reactors

The principles for building larger size systems are the same as above. Systems for bovine dung, vegetable, abattoir, and poultry wastes as well as urban solid wastes (USW) use the same concepts except for the degree of pre-treatment, urban solid wastes, requiring the most. The technologies almost always use high rate biomethanation (37 or 55°C reactors) but can be wet (a maximum of 15 % solids) or dry (25 to 35 % solids), and one or two-step. There are also minor variations in the scheme of operation. In the European scene, the number of wet and dry systems are about the same, but increasingly the dry systems are gaining prominence. While the advantages of two-step digestion process are recognized, most systems built till day are one-step systems. All the large systems are with continuous operation with adequate controls and instrumentation to monitor the performance of the systems.

The systems built in India till date have had input from European sources and in fact many have been built largely based on one technology called BIMA (short form for Biogas Induced Mixing Arrangement) digester design from Europe. The specialty of this design is the way mixing is performed with a concept that uses fluid dynamics without active mixing devices to cause mixing that enables handling of scum and high solids concentration fluids. This is illustrated in Figure 5.10. The digester has two compartments - one relatively small top section and the other bottom section with the two separated by an impervious diaphragm. The top region is connected to the bottom through a long central duct that has openings to the sides at the bottom as also one/two short ducts dipping into the fluid in the bottom region. The gas off-take is connected to the top region. Gas can accumulate both in the bottom and the top regions. The gas built up in the bottom region exerts pressure to let the liquid in the top region to go up. Since this region is also connected to the engine through a gas holder the pressure here will be lower than in the bottom area. At a suitable time when the level difference between the bottom and top regions exceeds a value, the pressure is released by opening the separate gas line from the bottom to the top region (towards the left in the Fig. 5.10 called the automatic valve). This pressure equalization process causes the liquid in the top region largely to flow down the central pipe and move out into the fluid at the bottom. This process and some flow through other ducting causes mixing of the fluids and the scum is broken in this process.

5.8.1 Cattle dung power generation system

A 235 t/day bovine dung based plant using the BIMA digester has been established at a large dairy in Punjab, India (Singh, 2004). The schematic of various elements is shown in Figure 5.11. The infeed of cattle dung at 20 % total solids (47.6 t/day) is mixed with water at 140

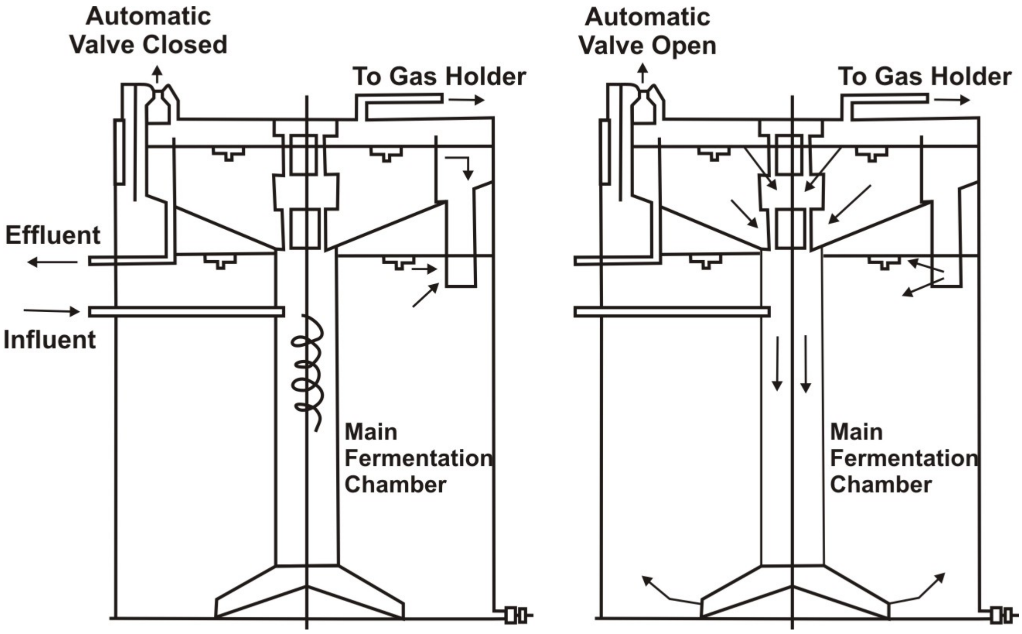


Figure 5.10: Cross section of a BIMA digester showing the mixing scheme of the fluids

t/day to bring the total solids content to 10 % and pumped into the BIMA digester of 10000 m^3 volume. The effluent from the digester is processed in a filter press to remove the particulates and the filtered liquid is further treated in an aerobic process to reduce the BOD. The final treated liquid goes to a clarifier for possible removal of fine particulate matter and taken off for discharge or re-injection into the system. The gas produced is taken to a large storage tank from where it is supplied to the gas engines for power generation. At 80 % volatile solids fraction, the volatile solids fed into the digester would be 30 t/day. The gas generation rate at 0.31 m^3 /kg VS would be 9300 m^3/day. The gas composition has shown 55 to 58 % CH_4. With Jenbacher engine of 1 MWe frame used in this plant at 39 % gas-to-electricity efficiency, the electricity generated would be 21000 - 22000 kWh per day. The volatile solid destroyed is about 55 % leading to an amount of 31 t/day (containing 13.5 t/day of VS) to be treated as compost. These values are also observed in operation. The energy efficiency of the digester's conversion process works out to 34 %. The project was built under an United Nations Development Program (UNDP)- Ministry of New and Renewable Energy (MNRE), Government of India initiative with the support of the local government at a total cost of the project was 2.6 million USD amounting to 30 USD/t-waste/yr or 2600 USD/kWe generated.

5.8.2 Vegetable market waste based power generation

The project on vegetable wastes at 30 t/day has been built using the same reactor design at the city Chennai, India (Bala Kameswari et al, 2007). Though there is a significant seasonal variation in the composition of wastes it is roughly 35 - 40 % banana stem and banana wastes, 20 - 25 % vegetable wastes, 15 - 20 % fruit wastes, 10 - 15 % flower wastes and other packing materials (hay, straw, paper, etc. 15 - 20 %). The pick up of stones, grit and plastics is < 1 % with a moisture content of 60 to 70 %. The total solids and volatile solids content were estimated at 20 - 30 % and 70 - 75 % respectively. The process flow sheet is presented in Fig. 5.12. The segregated wastes from the market complex are transferred to the receiving platform and lifted by a grab and further transferred into the hopper on to a belt conveyor. The wastes are

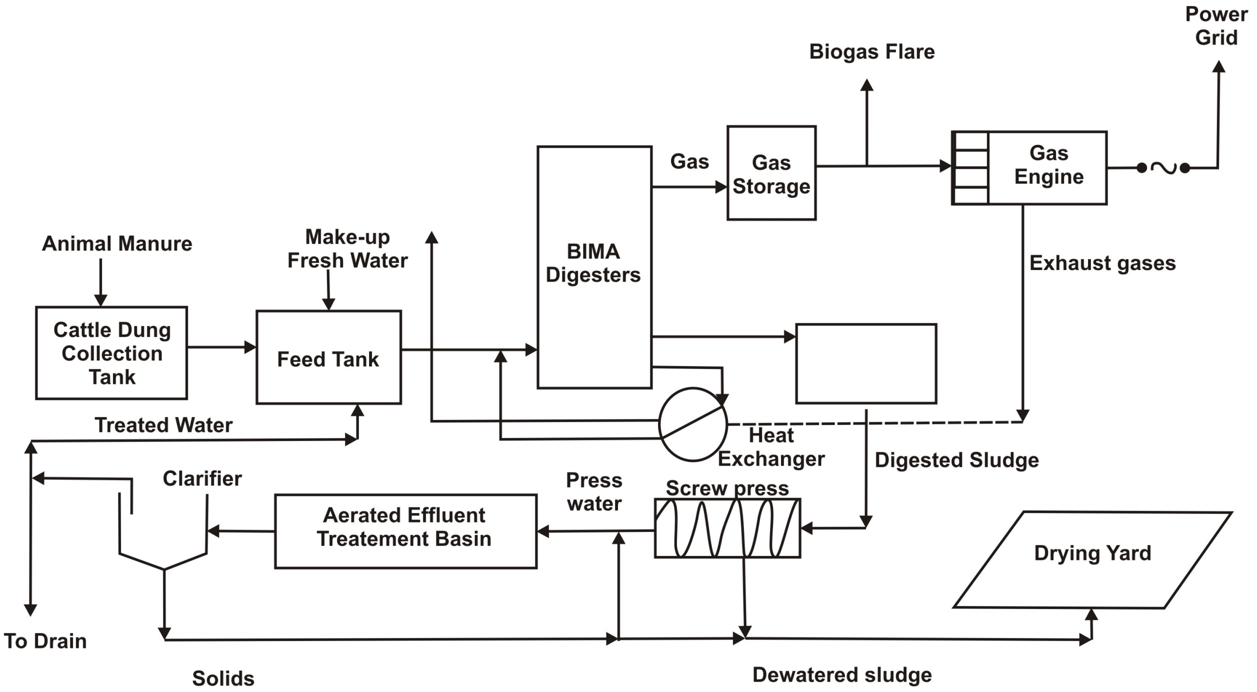


Figure 5.11: Schematic arrangement of various elements of a biogas based large power generation system in Punjab, India

taken this way to a shredder for size reduction to about 15 to 20 mm. The shredded waste is then blended with water from a screw press or freshly in a collection tank. The mixed waste passes through a macerator into the BIMA digester of 2650 m^3 volume. The biogas generated leaves the digester into a dry gas holder (530 m^3) made of a synthetic membrane (polyester). An in-situ biological desulphurization unit has been installed in the digester to reduce the H_2S concentration in the biogas below 500 ppm. The gas is drawn from gas holder by gas blowers and fed into the gas engine-alternator for electricity generation. The net power generated after in-house consumption is exported to local grid.

The residue from the digester is collected in an effluent buffer tank for de-watering. The digestate is pumped into a screw press by means of screw pumps and de-watered. The de-watered cake is discharged at the other end of the press. The cake from screw press is converted into manure through composting. Unlike the digester for cattle dung in Punjab discussed earlier, this reactor works at ambient temperature. Perhaps, it is thought that the ambient temperature in Chennai is close to anaerobic conditions throughout the year. The performance of the system is presented in Table 5.16. The performance of the plant seems to be very different from the original design. The design has a solids content of 25 % where as the actual solids content is 9.5 %. This also shows up in the overall power output that is less than half of the design value. Thus the system is far from reaching its intended performance. It is largely because the organic feedstock that the system was designed for has not been achieved.

The system was built with UNDP/MNRE assistance at 1 million USD amounting to 100 USD/t waste/yr or 4000 USD/kWe (on design) and about 8000 USD/kWe based on current performance. The primary difference between the financial performance of this project and the cattle dung project of Punjab is due to the scale difference (0.85 million tonnes/year on the cattle dung project). The revenue streams arise from the sale of electricity and manure. The NPK value of the effluents from specific streams is broadly shown in Table 5.17. The NPK values that these residues can provide falls short of what one obtains from state marketed chemical

Table 5.16: Performance details of Koyambedu plant at Chennai, India

Item	Design	Actual
Throughput, t/day	30	30
Makeup water, m^3/day	32.5	32.5
Solid loading, kg/m^3-day	3	
Total solids, t/day, %	7.5, 25	2.9, 9.5
Volatile solids (t/day), fraction, %	5.7, 74	2.2, 75
Retention time, days	37	37
Digester volume, m^3	2300	2300
VS destroyed, t/day	3	1.4
Reactor energy efficiency, %	53	63
Gas generated, m^3/day	2500	1140
Power, kWe	240	89
Gas generated/VS fed, m^3/kg	0.44	0.5
Energy generated/day, kWh/day	5250	2047
In-house energy used/day, kWh/day	470	770

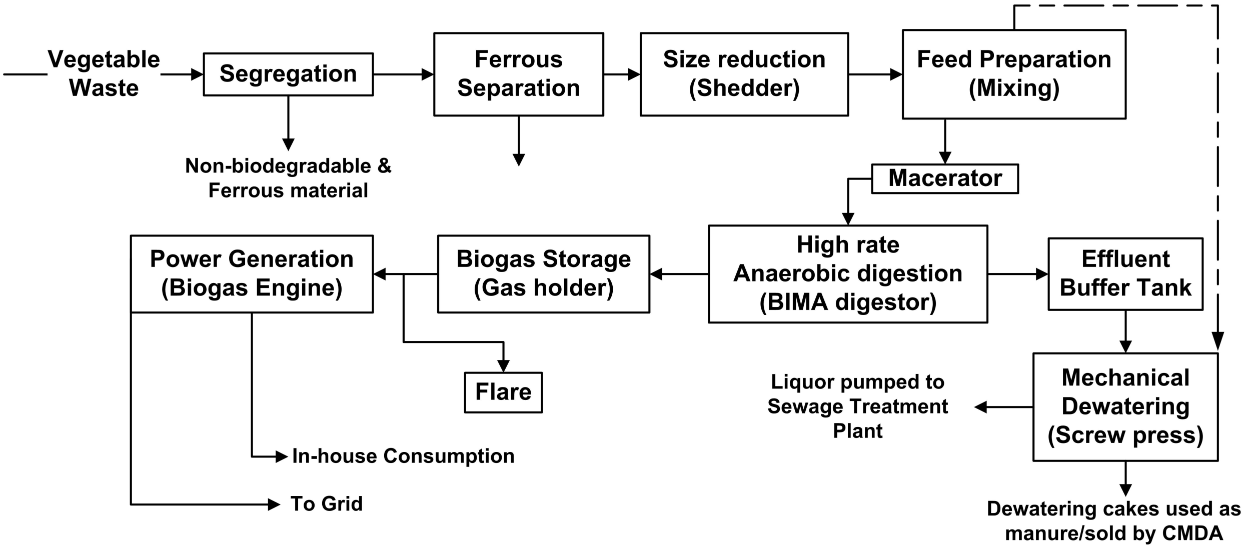


Figure 5.12: Process flow of Koyambedu (Chennai) vegetable market waste anaerobic treatment plant

fertilizers and this poses problems for the sale of the residues as fertilizers. They are sold as manure at much lower costs, perhaps lower than they may deserve in terms of benefits they provide for crop growth. These factors need to be kept in mind when the projects of this nature are conceptualized and implemented. It appears that the chances of these demonstration projects catalyzing private investments will be small.

5.8.3 Abattoir waste treatment

A major project on abattoir waste management has been implemented in one of the very large abattoirs in the state of Andhra Pradesh in India (M/s Al Kabir Exports Pvt Ltd, Hyderabad). It is of special significance because it uses both solid state digester (BIMA design) as well liquid effluent digester (UASB). Figure 5.13 shows the schematic description of various elements of the plant. The primary digester handles a variety of wastes - abattoir wastes, solid and liquid and dung from the animals as well as agricultural wastes to ensure that the plant parameters are

Table 5.17: The fertilizer value of some of the effluent streams (Internet, 2001; TERI, 2003)

Item	N, %	P, %	K, %
Vegetable market waste	2.1	1.6	2.4
Fruit and vegetable processing	1.2	0.07	0.64
Food wastes	0.5	0.13	0.26
Coffee pulp	1.8	0.1	3.0
Garden fertilizer, general purpose	10	10	10
Garden fertilizer, vegetables	10	20	20
Garden fertilizer, flowers	6	10	4

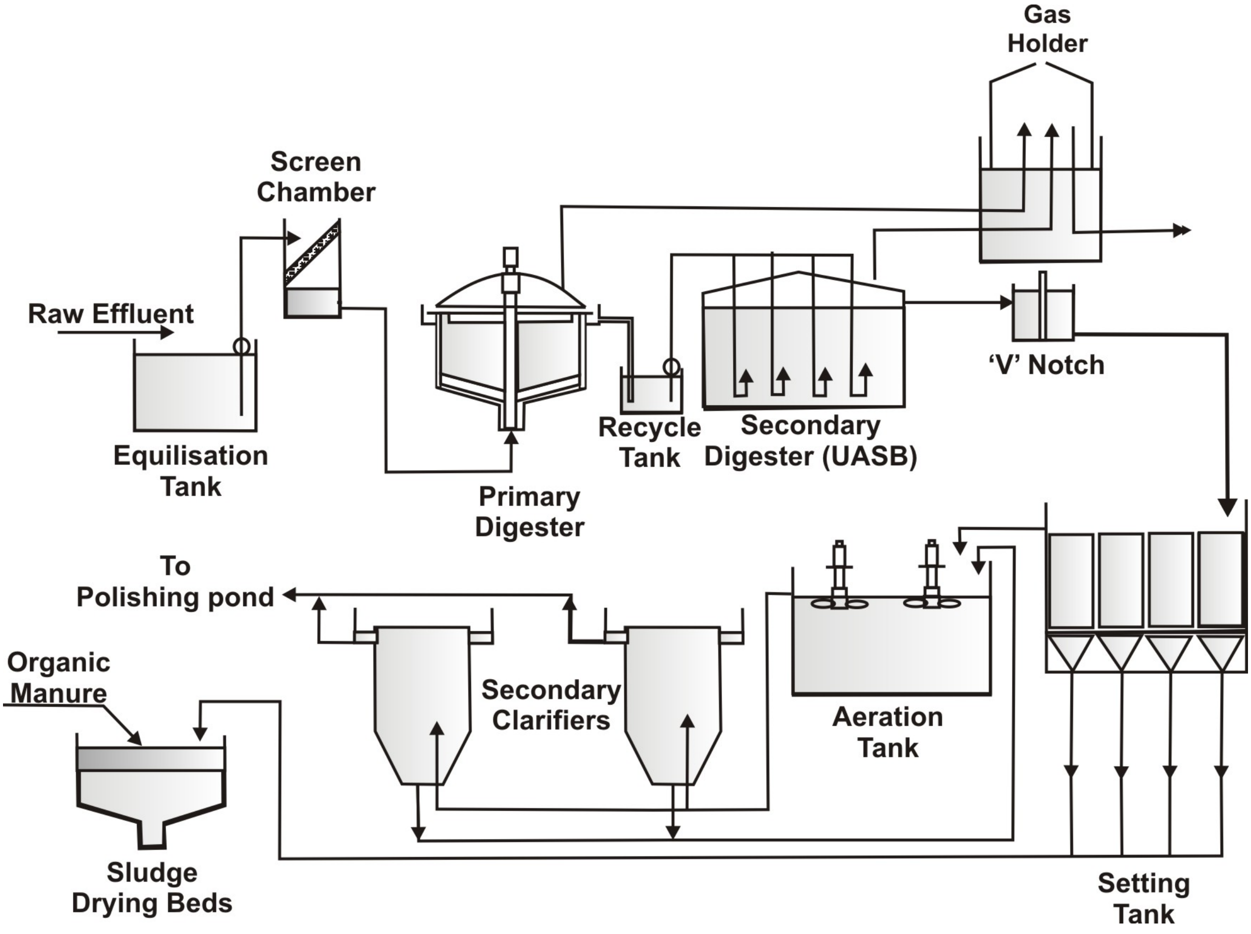


Figure 5.13: Schematics of the waste handling plant at an Abattoir

Table 5.18: Differences between substrates - USW, Sewage sludge,and Livestock wastes

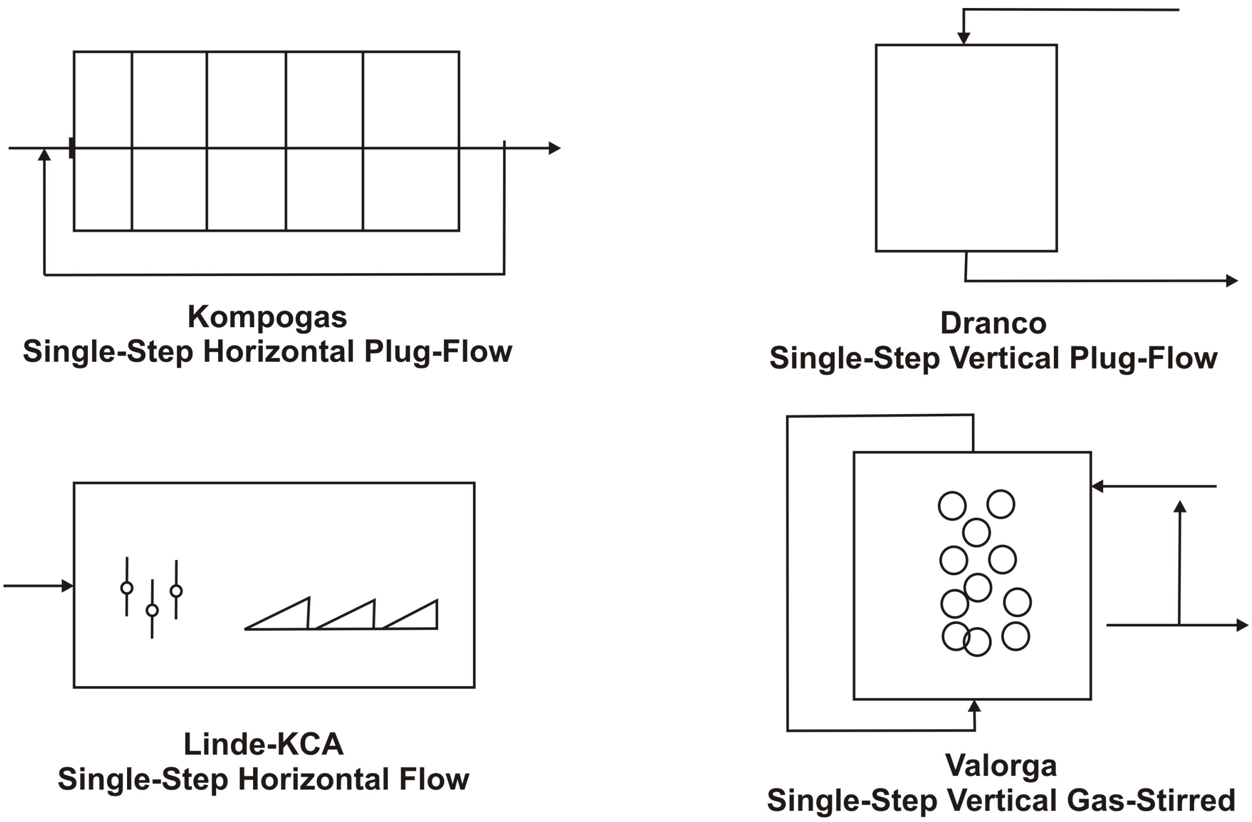
Feature	MSW	Sewage sludge	Livestock waste
Macro and micro-nutrients	Low	High	High
C:N ratio	High	Low	Low
Biodegradable matter	High	Low	Low
Dry matter	High	Low	Low

correctly balanced. It handles about (1400 m^3 liquids + 50 t solids per day) in a 2600 m^3 BIMA digester at a total solid loading of 8 - 12 % and a volatile solid loading of 3.6 t/day, The overflow from the BIMA digester is taken to a buffer tank. The overflow material is then transferred to vibration filter press for de-watering and the concentrate produced is taken back to the UASB treatment plant. The gas from UASB treatment plant also goes into the gas holder. The feed into the UASB digester is a liquid with COD of 3 - 4 kg/m^3 and the UASB reactor reduces the COD by 85 % with a retention time of 24 hours. The gas generated here is 0.35 m^3/kg COD destroyed. The total system gas output is 1800 - 2300 m^3/day at 0.55 m^3/kg of VS fed into the digester. The gas is used as the source of heat in a boiler. The de-watered cake is converted to bio-manure (NPK values are 5, 0.4 and 0.8 %) and sold. The effluent from the UASB digester goes through an aerobic treatment to reduce the BOD and COD goes into ponds meant for pisciculture and agriculture over a land that is a part of the industry. The plant is considered to be performing to better than the specifications laid out at the time of design. This plant was also supported by UNDP/MNRE.

5.9 Urban Solid Waste (USW)

The treatment processes for municipal solid waste have far more extensive pre-treatment section. Firstly, the unsegregated wastes that are collected and transported to dump sites have already spent anywhere up to 2 days either at home or on the streets causing generation of malodorous smells due to aerobic digestion processes beginning to occur. While most overseas plants have a sheltered receiving yard that in most cases have a air suction through the building to ensure prevention of spread of smells, such arrangements are usually missing in India. The dump yard is usually an open area. The smell and sight are both disagreeable. These have led to justifiable protest by communities living around the dump area. In fact several dump sites have been shut down due to public protest making it imperative for the shift of the location to even more distant location. This makes the transportation of wastes even more expensive. Much more holistic thinking is required if waste-to-energy projects have to succeed in India.

There are differences between USW, sewage sludge and livestock wastes as shown in Table 5.18. The fact that C:N ratio is vey high for MSW but low for others is the feature that is capitalized upon to mix the substrates to get to the correct range of C:N - 25 - 30. The fact that the dry matter content is high in MSW certainly for about eight months an year makes thermochemical conversion strategy a very important competitor both on technical and economic grounds, a feature that will be pursued later. Many variants of technologies are practiced in Europe - wet single step, dry single step, wet two-step and others. These are discussed excellently by Beck (2004) who has investigated most of the european systems. The number of wet one-step processes is small because diluting the MSW to $<$ 15 % total solids requires a large digester volume and is more expensive to build. Wet two-step processes also have limited applicability because of much higher capital costs except in the case of MSW along with sewage sludge.


Kompogas
Single-Step Horizontal Plug-Flow

Dranco
Single-Step Vertical Plug-Flow

Linde-KCA
Single-Step Horizontal Flow

Valorga
Single-Step Vertical Gas-Stirred

Figure 5.14: Schematics of several digester concepts from Europe

In dry systems, transport and handling of the wastes is with conveyor belts, screws, and powerful pumps especially designed for highly viscous streams. This type of equipment is more expensive than the centrifugal pumps used in wet systems but it is also more robust and flexible in as much as wastes with solids content anywhere between 20 and 35 % can be handled. In such systems, at least in the process of digestion itself, impurities such as stones, glass or wood do not pose problems of the same kind posed by wet systems. The principle pre-treatment necessary is the removal of the coarse impurities larger than 40 mm. This can be accomplished either via screens, as is typically the case with mechanically-sorted MSW, or via shredders in the case of source-separated biowaste. Any heavy inert materials which pass the pre-treatment need not be removed. This makes the pre-treatment of dry systems somewhat simpler than that of their wet counterparts, and probably more attractive for the biomethanation of MSW, which typically contain 25 % by weight of heavy inerts. A comparative schematics of four large scale systems manufactured in Europe (Kompogas, Dranco, Valorga and Linde-KCA) operating with solids concentration of 28 - 35 % are presented in Fig. 5.14. These one-step dry processes being commercially used are distinguished by the material flow approach (horizontal-flow, vertical down-flow or upflow), the method of heating (steam injection or heat exchanger), and the mixing method (recycling, radial mixing, transversal mixing, or comprehensively mixed by gas injection). Most of the systems work at mesophillic or thermophillic range and have a residence time of 20 - 24 days. The system elements of one of the processes is shown in Fig. 5.15. The Linde-BRV process is based on a plug-flow concept. A mass balance of one of the typical systems (drawn from Beck, 2004) is shown in Fig. 5.16. Even though the waste is source-separated, 83 % qualifies for biomethanation. The gas produced is at 0.15 m^3/kg waste and the electricity generated is 1.15 kWh/m^3 of the gas. Apparently, the engine used is of an earlier generation for modern day engines give 1.8 to 2 kWh/m^3 gas. The data of a number of large power plants has

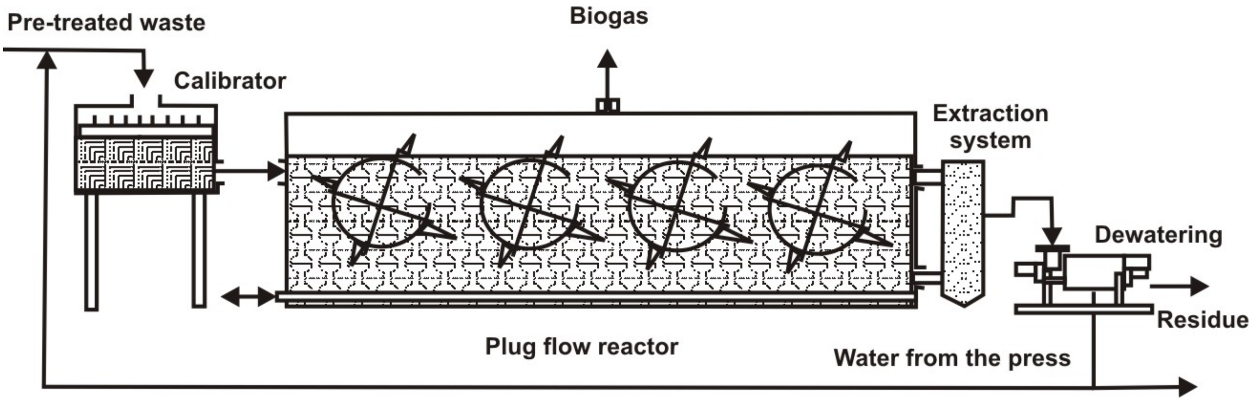


Figure 5.15: The system elements of one of the european processes - Linde-BRV process

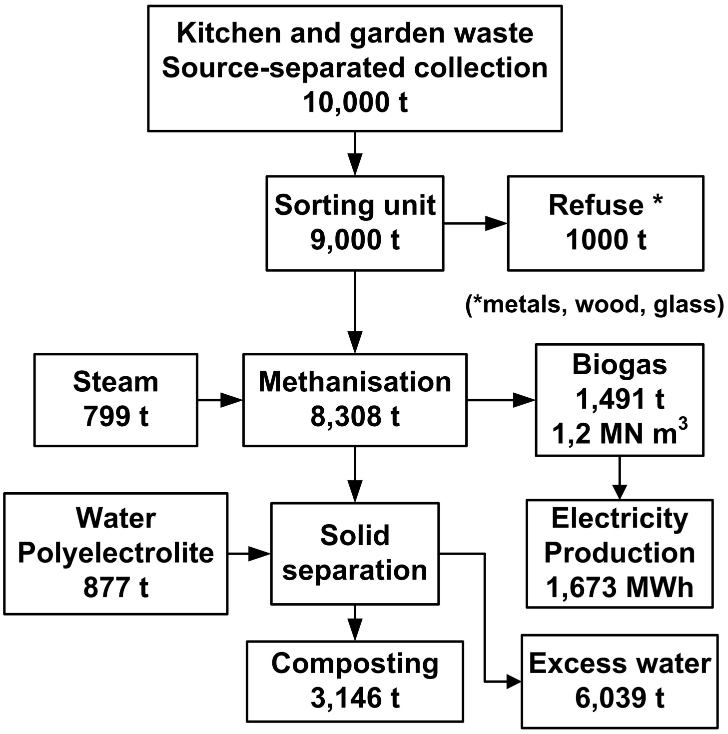


Figure 5.16: The mass balance of one of the high temperature digesters

Table 5.19: Performance of a number of AD plants of Europe; Y = Yard, F = Food, K = Kitchen, B = Biosolids, M = Manure

Location	Waste	Waste	Dig vol	OLR	Gas	Gas/dig vol	Gas/waste
	Type	t/yr	m^3	kg/m^3-d	m^3/d	m^3/m^3-d	m^3/kg
Aaburg	Y	12128	1500	22.2	2215	1.48	0.067
Beer	Y	4410	480	25.2	1038	2.16	0.086
Bachenbach	Y + F	9482	520	50.0	2323	4.47	0.089
Badenbaden	F + K	7166	6000	3.3	3965	0.66	0.202
Braunscweig	K	17640	1680	28.8	4647	2.77	0.096
Buchen	MSW	110250	4000	75.6	10936	2.74	0.036
Geneva	Y	13230	1030	35.3	3284	3.20	0.091
Grindsted	B + F	38036	2800	37.2	1774	0.63	0.017
Holsworthy	M + F	160965	8000	55.2	10673	1.33	0.024
Karlsruhe	Y + K	8820	1350	17.9	2390	1.77	0.099
Lengo	Y + K	37485	2650	40.3	10456	4.10	0.102
Munchen	Y + K	27563	2460	30.7	4105	1.67	0.054
Nederuzwil	Y	11025	900	33.6	2378	2.64	0.079
Olefingen	Y	13781	840	45.0	3005	3.58	0.08
Rumlang	Y + F	7718	460	46.0	2184	4.75	0.103
Samstagem	Y + F	8489	520	44.8	2238	4.31	0.096

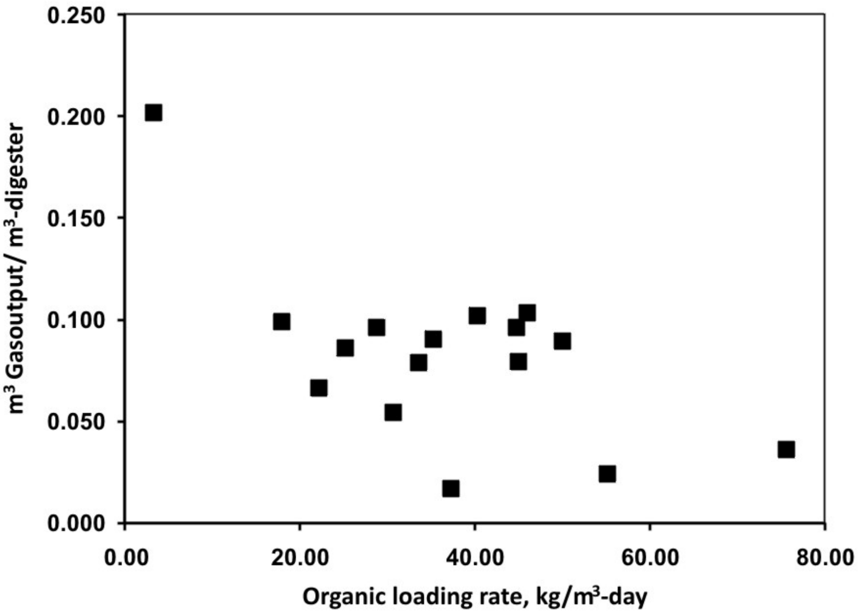


Figure 5.17: The variation of gas output per unit digester volume with organic loading rate

been presented by Beck (2004). These are collated and performance indicies derived to examine the overall performance of these plants are presented in Table 5.19. The relationship between the organic loading rate (OLR) and the gas output per kg waste for these data is set out in Fig. 5.17 is revealing. As the OLR increases the gas output per kg waste decreases. Most systems use an OLR between 20 and 50 kg/m^3-day and the scatter in performance is partly contributed by differences in input concentration (volatile solid concentration, kg/m^3) not accounted for here because of lack of information. In any case, the variation in the performance of the plants is much wider than can be accepted in any engineering system design, even allowing for the fact that the functioning is dependent on bacteria of a wide spectrum. Two-step digesters are argued to be much better in terms of OLR or VSR (depending on whether a liquid or solid waste is being treated) [Klass, 1998]. Yet the share of two-step digesters has to increase in the market.

5.10 Overall performance

Table 5.20 summarizes the performance details of several systems discussed above. The digester volume required to treat the waste varies widely depending on the residence time adopted for the treatment. This is about 24 hours for liquid effluents but can vary between 12 days to 24 days with different designs that use mesophyllic or thermophillic operating temperatures. While the gas output is 20 to 40 m^3/t (20 - 40 g/lit) of wastes for low efficiency designs and operations, it is 60 to 200 m^3/t for well operating larger systems (see also Table 5.19). The large in-feed for the case of abattoir is due to liquid nature of the waste. The amount of water demanded from other plants is also large and such plants are therefore most appropriate if the waste has a very large liquid content.

5.11 Summary

This chapter has been concerned with anaerobic treatment of domestic and industrial wastes. Both these can be largely in liquid form - sewage and kitchen wastes from the domestic sector. Solid wastes can also come from kitchen and gardens. Liquid industrial wastes arise from food processing units in a wide variety - alcohol, milk, fruit, starch and meat, as well as paper and pulp. Solid wastes come from vegetable markets, poultry, urban dwellings and other industries. Anaerobic treatment is perhaps the only alternative for primary treatment of liquid wastes. These systems can be designed for removal of the organic matter to large extents - 75 to 90 % with reactors designed for a residence time of 24 to 30 hours. This requires that the reactor be operated at 37 or 55°C. The desirability of this operation is due to reduced reactor volume and hence investment cost. Operational problems may rise due to imbalance of pH, C:N balance and specific nutrients. Continuous online monitoring will be valuable for maintaining the desired optimal performance. Maintaining the correct range of parameters is performed by mixing other waste streams.

The case for treating waste streams with solids content better than 50 % and perhaps >30 % and rest water by anaerobic digestion is less clear. International effort has gone into building systems for these substrates as well. The performance is highly varying and coupling the waste treatment with disposal of final solids - the compost has led to problems of commercial operability of the plants particularly in India. It is found most desirable to focus on a product (electricity, in most cases) which brings in adequate revenue and if there are sub-products (like manure or final waste water or both), manage them without having to depend on a public client significantly. Alternate approaches that are technically feasible and commercially viable must be approached in an open way to ensure waste management as a reliable revenue stream.

Cattle manure based plants at domestic level have been highly lauded both in India and China for domestic cooking applications. Much is discussed of the benefits in broad terms. The development as envisaged has needed continuous Governmental support something not sustainable on a long term basis. It is not sufficiently well realized that the essential problem is related to the technology. Converting about 25 – 35% of the volatile solid (in an annual mean) that is the energy carrier at non-optimal temperatures and conditions with an enormous residence time (30 days) and expecting commercially meaningful performance of the system seems

Table 5.20: Summary of performance of field systems, VS = Volatile solids, /d = per day, F.water = Final water

Feedstock	Infeed t/day	Dig vol m^3	VS loaded t/d	Gas m^3/d	Energy kWh/d	Sludge (VS) t/d	F.Water t/d
Cattle dung	0.05	2	0.0075	1.5	2 - 3	0.04 (0.006)	0.09
Cattle dung	235	10000	28	9240	22000	27 (18)	70
Veg waste	30	2300	2.2 (5.7)	1095	2300	60 (0.8)	15
Abattoir	1450	2640	9.2	2000	Heat	1340 (7)	1040
Dranco	140	3150	30 - 35	16800	24000	46 (8)	58
Valorga	145	6600	20 - 25	8100	16000	70 (10)	40

too much to expect. Part answer lies in using substrates like starch and food wastes with carbohydrates to reduce the residence time. This is the approach taken by ARTI (*www.arti.org*) and the system design with <3 days residence time is commendable. Further performance improvements may even be possible and might make the product far more attractive commercially. A commercial challenge that appears would be the possibility of a solid fuel based cook stove that can hold on to high efficiency and low emissions. If this happens, the technical question would be whether the combined benefits of a biogas digester that needs far more attention and care with a residue that is to be humus and manure will be more appropriate and attractive than a stove with processed fuel supply when one deals with the issues in a holistic manner.

Other developments in India involving leafy biomass and urban solid wastes have issues of the kind described just above. Efforts need to be made to ensure ownership by a private industry, at which time several technical aspects get greater focus and competing technologies of waste-to-energy need to be accounted for.

An interesting new aspect uncovered is a non-dimensional number defined by M = (OLR/COD) t_{res} or (VSL/VSC) t_{res} (OLR, VSL = Organic loading rate, Volatile solid loading, COD, VSC = chemical oxygen demand, volatile solid concentration) that reflects the operation of anaerobic digesters and the % COD removed or % converted will depend on M, the single parameter. This is being emphasized because literature is abound with the three parameters treated in an independent way.

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6 Gasification

6.1 Introduction: Why gasification when we have combustion?

Chapter 3 on the routes to energy conversion has already introduced the elements of gasification - a process by which solid fuels are converted to gaseous fuel by thermochemical means. A question that arises commonly is: if we can perform clean combustion directly why do we need to deal with converting to gaseous fuel?

Combustion releases the energy into high temperature product gas that is used locally. Combustion efficiencies with biomass combustors can go up 98 % when managed with controls. But then, one needs to use 10 to 15 % excess air to ensure this class of efficiency. This will effectively raise the amount of biomass used to get the product - steam for power generation or metallurgical output from melting metals or food from cooking.

The product of gasification is however a fuel gas. It can be further used for combustion purposes either locally in a furnace or at a distance from the location of gasification in a wider variety of applications like reciprocating or gas turbine engines, fuel cell or as a feedstock for conversion to liquid fuels like methanol or biodiesel. The gasification process itself has an efficiency of 65 to 90 % of conversion to gaseous fuel depending on the fuel, with wood and solid residues leading to efficiencies of 85 to 90 % (throughput dependent) and rice husk and high ash fuels around 65 to 70 %. This gasification process can be conducted with air or oxygen - steam mixtures with different objectives. Air gasification leads to a gas called *producer gas* with a dry gas composition of CO and H_2 of about 20 %, CH_4 of about 1 %, CO_2 of about 12 % and the rest nitrogen. The gasification process conducted with oxygen and/or steam leads to gas with 20 to 35 % CO, 30 to 40 % H_2, and 15 to 25 % CO_2. This gas is called *synthesis gas* and it forms the feedstock for producing alcohols or hydrocarbons.

The specialty of the gasification process is that it can be used for getting electricity even at low power levels (a few kWe to a few MWe) from reciprocating engines at good efficiencies of gas-to-electricity (and so biomass-to-electricity) something that would be impossible with combustion-steam route. To exemplify this feature, at 10 to 200 kWe power level, biomass-steam-electricity would give 3 to 5 % efficiency (implying a biomass per kWh consumption of 4.5 to 7.5 kg/kWh) and biomass gasification-reciprocating engine power generation will give conversion efficiencies of 18 to 22 % (implying a biomass per kWh consumption of 1 to 1.3 kg/kWh).

The fundamental reason for this situation is traced back to thermodynamics. When we burn biomass or the producer gas we get peak temperatures of 1400 K. This raises the working fluid - steam to temperatures of 700 to 800 K in small steam generators with working pressures of less than 0.2 MPa ($\sim$20 atm) running the turbine. Because the peak cycle temperature is low (800 K), the efficiency is low [Carnot efficiency is 1 - (ambient temperature (K)/maximum temperature)]. When we use the gas in a reciprocating engine, the peak temperatures achieved in the combustion chamber of the engine would be close to 1400 K. Hence we get better efficiencies. The limitations on achieved efficiency in these cases arises from systemic losses that are more significant in reciprocating engines than in turbomachinery.

Biomass-to-electricity in larger systems $\sim$ 3 MWe or more through steam route are moderately efficient - 20 to 24 % due largely to the use of superheated steam at higher operating pressures - 4 to 6.5 MPa. Higher power systems ($\sim$ 30 - 50 MWe) use even higher pressures (up to 90 atm) and higher superheat allowing achieving of efficiencies up to 30 %. Part of the reduction in achieved efficiencies in such systems arises from lack of care to use "dry" biomass. By using wet biomass - 25 to 50 % moisture, there are two classes of "losses". One needs to put in energy to vaporise the moisture in the biomass and raise it to the flame temperatures. Another loss is that this reduces the peak temperature achieved in the furnace/combustion chamber and effective reduction in heat transferred to the steam in the boiler. Some very large power generation systems with forest biomass built in the USA [see Table 4.11 and the article of Overend in Sims and Aliyagh, 2003 for more description] and Canada suffer these losses. Preheating air and pumping the air into the combustion system may improve the operational reliability, but the evaporated moisture is inside the system itself. In fact, if the preheated air is used to drive away the moisture before the biomass enters the main combustion system, the efficiency improvements will be achieved.

The gasification route to energy can be treated as a two-stage combustion process. All the air required normally in a combustion process, typically about six times the biomass throughput is not to be introduced at once in a gasification process. The gasification process uses about one-third of the air required for combustion and generates cooled combustible gas a little less-than-half of what is generated by combustion process. This gas then is burnt with air about 1.2 to 1.4 times the gas flow rate with the air flow rate matching with the air required for burning the biomass at stoichiometry.

This approach of staging the conversion process enables the emission abatement process to be dealt with more economically as the flow rates handled are much lower (half of that in the case of combustion). Any further treatment can be dealt with during the combustion process of the gas more easily because these methods are much simpler to handle (also, they are better understood). When handling treated waste wood from demolition of structures, combustion process is considered risky because it will be difficult to deal with the emissions. In such cases, gasification process offers distinct advantages due to multi-point control possible without loss of efficiency.

There are many metallurgical processes involving reduction of oxides that need gases like CO and H_2. For producing these gases natural gas is chemical source and subject to reformation to get these gases. When natural gas is unavailable, there is difficulty in conducting such operations. However, biomass based gasification systems can be used to generate CO and H_2 for use in the metallurgical process widening the scope of setting up of such plants outside the area of the availability of natural gas. There is a product called "tar" composed of oxygenated higher hydrocarbons of complex structure that gets produced in the gasification process in amounts that are not large for beneficial use and not small to be ignored. They are much higher for some class of air-gasification systems and for oxygen-steam systems as well. They get carried into the gas and get deposited in tiny spacings and locations of high velocity changes like valve seatings, turbosupercharger clearances, and the piston. They are very difficult to get rid of and hence, their generation being minimized is the best strategy. They form the bane of all gasification technologies (much more on this will be discussed later).

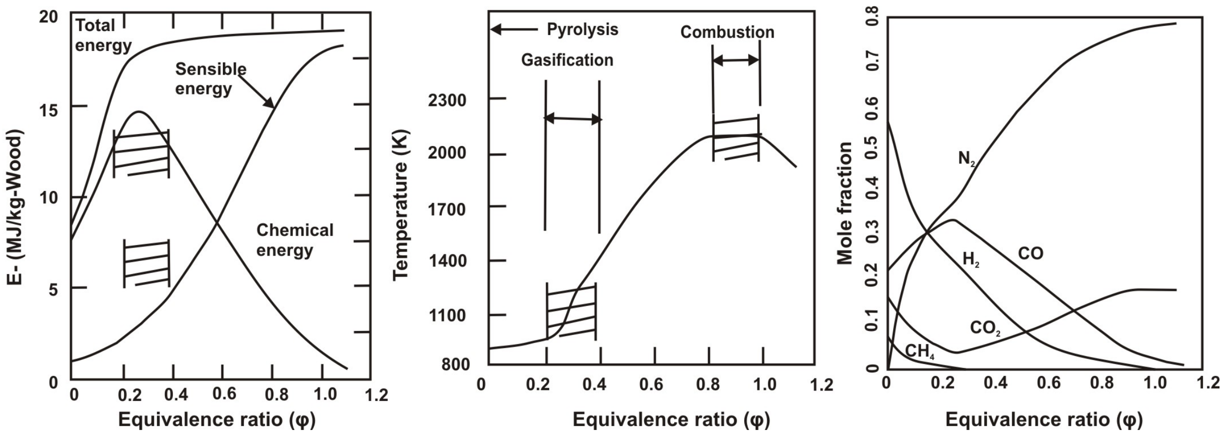

Figure 6.1: Variation of chemical and sensible energies as well as temperature with equivalence ratio, ϕ

6.2 Basic principles - chemical thermodynamics

It was described in Chapter 3 (section 3.8) that gasification is a combination of oxidative pyrolysis and hot char induced reduction reactions. Thus both oxidative pyrolysis and reduction reactions occur at fuel rich conditions. This means that the equivalence ratio, $\phi < 1$ for the gasification process. A standard and very insightful way of understanding this behavior would be to examine the variation of the energies, temperatures as well as composition with ϕ as shown in Fig. 6.1. The composition shown in this figure is only for gaseous components. At rich ϕ there will be liquid and solids remaining unreacted. The total enthalpy of sun-dry biomass is 16 MJ/kg as was indicated in Chapter 4 (section 4.5). When it is thermo-chemically treated with air at various equivalence ratios (various ϕ), the material will be transformed into char, liquids and gases. At ϕ = 1, the energy will express itself largely in sensible form leading to high temperature of the gases as evident in the figure on the right side. When the conversion process occurs at sub-stoichiometric levels, part of the energy will begin to get stored in chemical form - in the molecules of combustible gaseous fuels like CO, H_2 and CH_4 largely. Their fraction will continue to increase as one reduces ϕ. This process also reduces the equilibrium temperature indicating to the shift of storage of energy in chemical form compared to sensible form. This goes on up to ϕ = 0.25 at which point the chemical energy reaches a peak. The compositional variation in the last plot in Fig. 6.1 shows that CO reaches a peak at the same ϕ. In the shift of the composition from ϕ = 1, there will be some fraction of carbon left unreacted and some liquid fragments as well. At the peak of CO, the liquid fragment is indeed small (a few hundred ppm), but the fraction of carbon unreacted is not so small ($\sim$ 2 %). The fraction of CH_4 begins to pick-up as ϕ is reduced from this value. There will be increased fractions of liquid fragments in this region. In the domain of $0 < \phi < 0.25$, the process is significantly rate controlled and the composition of the products is dependent on the rate at which it is conducted; the limiting line ϕ = 0 corresponds to pyrolysis. It is observed that higher fractions of CH_4 will always be accompanied by higher fractions of higher hydrocarbons that lead to "tar". *In fact the magnitude of CH_4 can be used as an indicator of "tars"*. If CH_4 is about 1 %, "tars" will be low. If they exceed 2 %, it is almost certain the fraction of "tars" will be significant (more than about 500 mg/m^3).

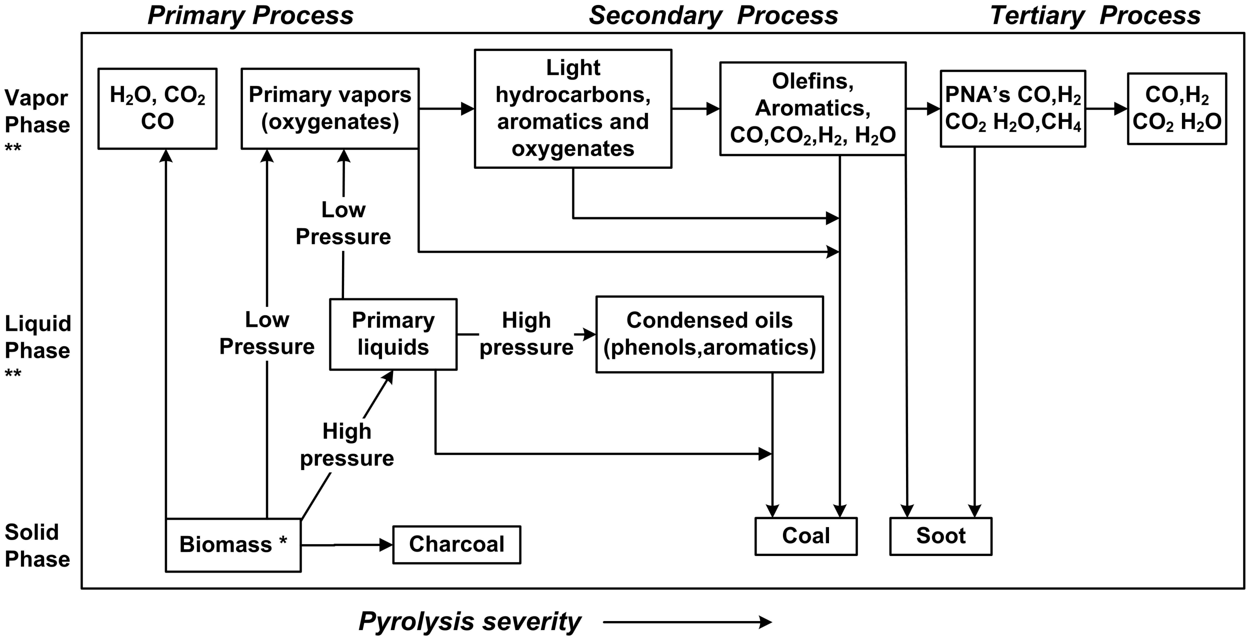

Figure 6.2: Different pathways of pyrolysis in biomass. Note the three sets of pyrolytic reactions - primary, secondary and tertiary and the chemical components, PNA = Poly nuclear aromatics, drawn from Milne et al, (1998)

6.3 The thermochemistry of gasification - early part

The conversion process involves many steps: (a) heating up of biomass that involves loss of moisture both unbound and bound. These occur at temperatures of less than 200°C. (b) Volatile generation from biomass that begins when the surface reaches 350 to 400°C. If the heating rate is small as will happen in most fixed bed systems that use relative large size biomass (20 to 70 mm), the depth over which the volatile generation occurs is larger. In this case, the passage of volatiles through the char crevices will cause further reactions of the volatiles with the char (called secondary reactions). On the other hand, if the particle size is small (less than a few mm) and/or heating rate is high as it happens in fast pyrolysis processes, the entire particle will attain the temperature at once and release volatiles. (c) The gases and volatiles that arise from the processes (a) and (b) will be different. In fact, the chemistry of gasification is strongly linked to the rate of local temperature rise and the residence time the gas has in the reactive medium, in this case, char.

The various pathways of conversion are shown in an excellent diagram presented by Evans and Milne (see Milne et al, 1998) in Fig. 6.2. There are three parts, namely, the primary, secondary and tertiary processes. Primary processes involve direct devolatilization from the surface. The secondary pyrolysis process is due to the reaction of the primary products that consist of CO, CO_2, H_2O, and complex oxygenated higher hydrocarbons with char. The products undergo further reactions of decomposition, association in the presence of hot char leading to tertiary compounds. These consist of CO, H_2, CH_4, CO_2 and more complex polymerised compounds. The pathways by which the volatiles get processed in the high temperature environment is oxygenates (350 - 450°C) $\Rightarrow$ phenolic ethers (450 to 550°C) $\Rightarrow$ alkyl phenolics (550 - 650°C) $\Rightarrow$ heterocyclic ethers (650 - 750°C) $\Rightarrow$ poly-aromatic hydrocarbons (750 - 850°C) $\Rightarrow$ larger polyaromatic hydrocarbons (850 - 950°C). Figure 6.3 shows the structure of the principal tar components.

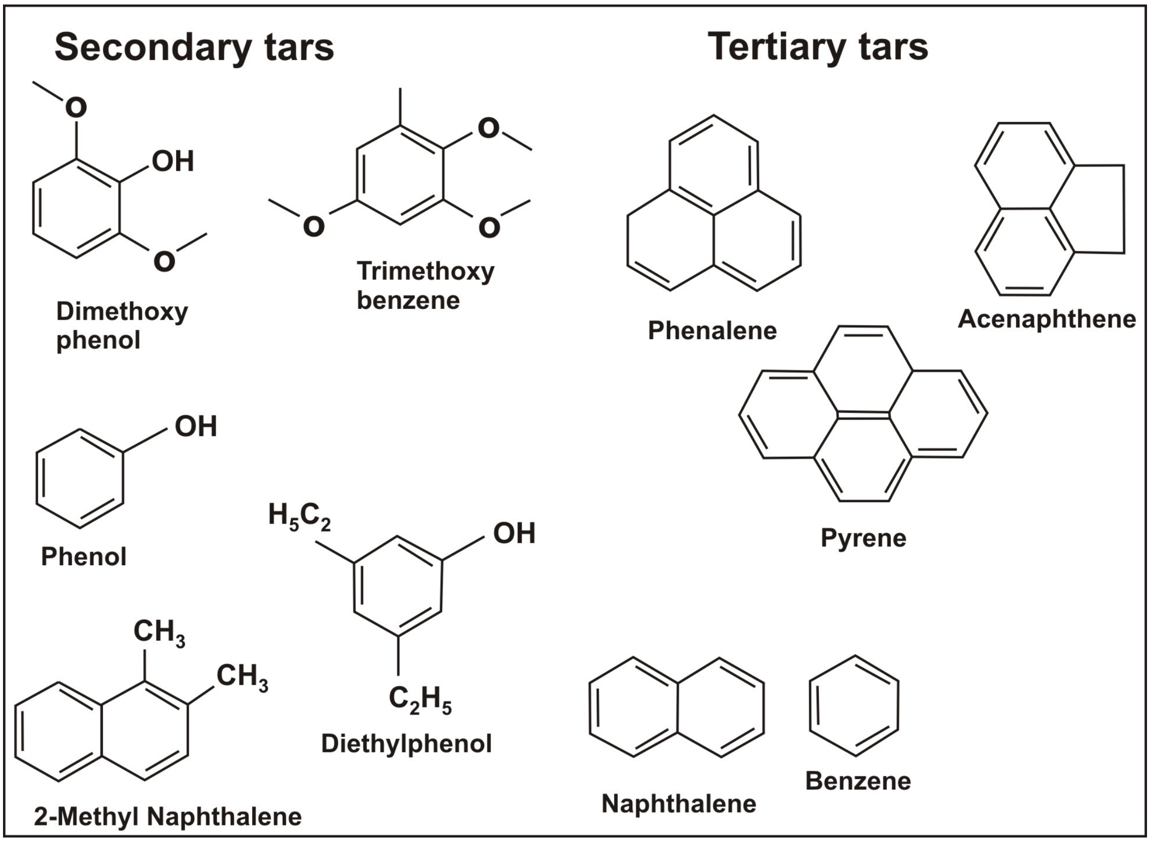

Figure 6.3: The structure of tar components - secondary and tertiary

Since the aim of the gasification system is to produce clean gas, the gasification system is considered poor if it produces significant volatiles with little “cooking” like in updraft gasifiers (discussed below). A good gasification system will carry through the gases and volatiles in a bed of hot char with sufficient time for tertiary pyrolysis reactions to proceed enabling the conversion of smaller problematic fragments of the oxygenated compounds to simpler non-condensible reactive gases like CO, H_2, CH_4 largely with very little of higher hydrocarbons.

Clearly, gaseous components are more significant at ambient pressure (low pressure in the figure) than at high pressure as illustrated in the diagram. This is because higher pressures prevent reaction pathways toward smaller fragments.

If one were to estimate the time required for the piece of biomass to heat up to pyrolysis temperature (conduction time largely), for a 10 mm size particle it is about 20 - 30 s. *The conduction time varies as the square of the size described by* $t_{cond} \sim$ *(size)*^{2}. For a 0.1 mm size particle, this time is 2 - 3 milliseconds. And a 50 mm size particle has a conduction time of 500 - 750 s (8 - 12 mins). If we note that the surface has to heat up to 400°C in this time, the temperature rise rate is about 30 - 45°C/min. Experiments on thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) have been conducted with powders of biomass of 100 microns or less to ensure that the entire particle is at the same temperature in determining the weight loss rate of the parent material (biomass as well as its structural fragments) and the evolution of various chemical species without differential temperature effects. Typical heating rates used in these experiments are 10°C. Amongst very many studies performed on the subject, an insightful set of results from a recent study on TGA and DSC on the structural components of biomass (cellulose, hemicellulose and lignin) are set out here (Yang et al, 2007). Figure 6.4 shows the plots of mass loss and the differential heat (defect or excess) vs. temperature at heating rate of 10°C drawn from a recent study by Yang et al (2007). This study examines the behavior up to 900°C and the variation of the gaseous components as well. The decomposition of hemicellulose and cellulose seem to occur in significant measure sequentially between 220 - 315°C and 315 - 400°C.The decomposition of lignin occurs over a much broader range - between 160 to 900°C. The reason for a wide range of reactivity of lignin is its structure having a wide range of aromatic rings of varying complexity that even at relatively low temperatures some simpler structures break down and some other fragments do not breakdown even at high temperatures since other structural elements are strongly interlinked. In contrast, both cellulose and hemicellulose are structured in a simpler measure. It is the significant decomposition of hemi-cellulose up to about 250°C that is responsible for torrefaction process (to be discussed subsequently). While about 45 % lignin, 20 % of hemicellulose remain even at 900°C very little of cellulose remains beyond 600°C. The results of differential scanning calorimetry shown on the right are also revealing. Cellulose has a significant endothermicity and hemicellulose and lignin are exothermic at temperatures not far removed from the devolatilization zone (300 to 400°C). This difference in the thermal behavior can explain the impression that biomass in phase change conditions is sometimes thought mildly exothermic and other times mildly endothermic. The reason is that biomass is composed of different amounts of its structural components and these can give different levels of exothermicity depending on the actual composition.

The generation of gaseous fragments during pyrolysis for cellulose and rice husk drawn from the study of Sonobe and Worasuwannarak (2008) is presented in Fig. 6.5. The production of the gases starts from around 300°C for cellulose, but at 220°C for rice husk (and 180 and 220°C for rice straw and corncobs not shown here). These correspond to the breakdown of hemicellulose. While most fragments are generated in the significant weight loss zone, hydrogen generation picks up and continues for much higher temperatures. Clearly, these are the consequence of continued vapour phase reactions that occur at higher temperatures over longer periods. It is these species that are also found in the early part of the gasification process augmented in addition by the presence of oxygen in the gas phase.

The information obtained from the weight loss with temperature can also be interpreted as with time since the heating rate is constant, Methods of converting this information into kinetic data that can be used for modeling is next step. for this purpose, a kinetic model has to be set up. There are several models conceived for this purpose described in a review of pyrolysis models by Prakash and Karunanithi, (2008). A typical model due to Koufopanos et al (1991) that accounts for both primary and secondary pyrolysis pathways is shown in Fig. 6.6. In this description, the details of the reactant volatiles as well final products are not provided. They can be obtained in a subsidiary way through simple stoichiometric relations. The reaction rates are described by $dX_i/dt = A_f {X_i}^{n_1} exp(E/RT)$. In this equation, X_i is the mole fraction of the specie i, A_f is called *the frequency factor*, n_1 is the order of reaction taken typically as 1 here, E/R is called the *activation temperature*. For other reactions in Fig. 6.6 one can write similar expressions. The actual values of the parameters are derived from the TGA data. The kinetic processes are generally sensitive to the presence of catalysts. Many inorganic compounds present in the biomass qualify for being catalysts. Thus, the kinetic parameters differ considerably depending on the biomass and some times, the same biomass grown in a different geographical area. Typically, the activation temperature will be 10000 to 25000 K. These values are so large that the kinetic rates will be very sensitive to the temperature. However, when the thermochemical conversion process occurs in large reactors the size of the feedstock is of much larger size, the processes of heat and mass transfer will exercise control as well. When these exercise control, the effects of kinetics will get moderated significantly. This is often not realized and

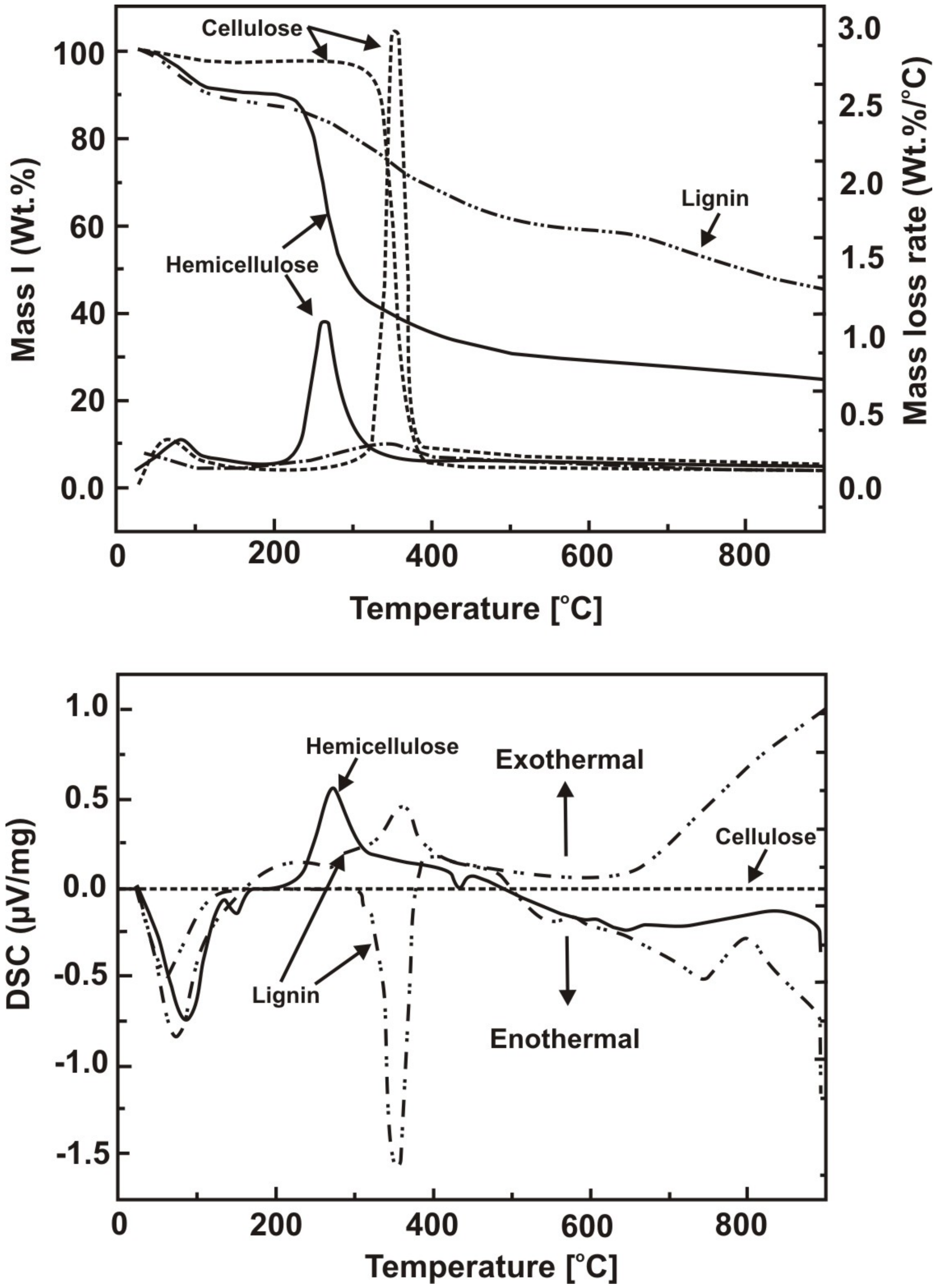

Figure 6.4: The TGA and DSC results for cellulose, hemi-cellulose and lignin at a heating rate of 10°C - less than 100 μm, 5 mg samples (from Yang et al, 2007)

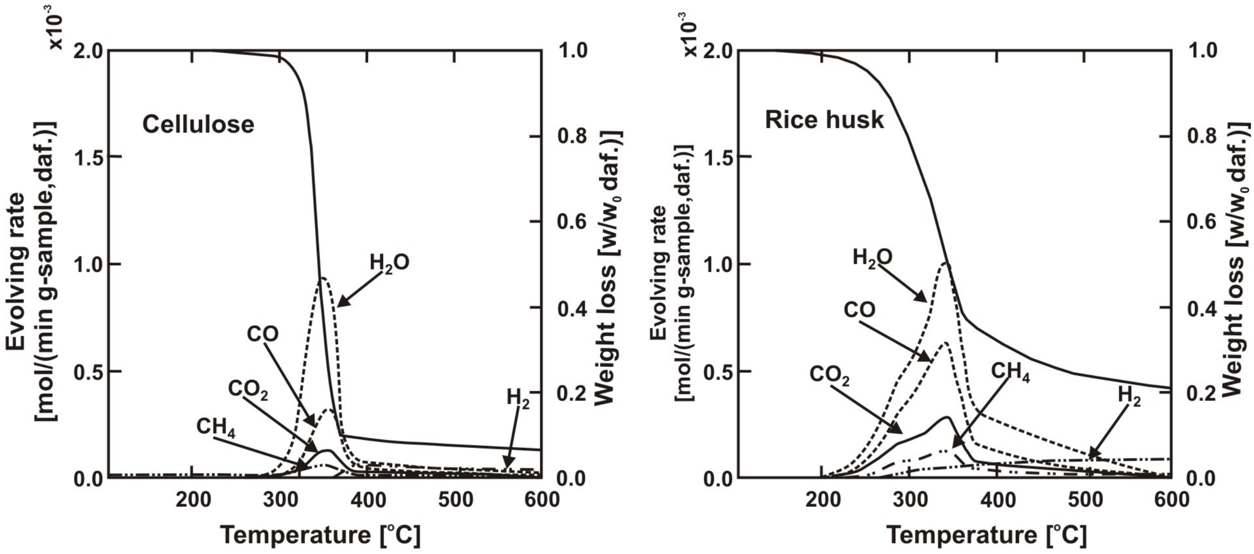

Figure 6.5: The production of CO, CO_2, H_2, H_2O, CH_4 during the TGA experiment for cellulose and ricehusk (drawn from Sonobe and Worasuwannarak (2008)

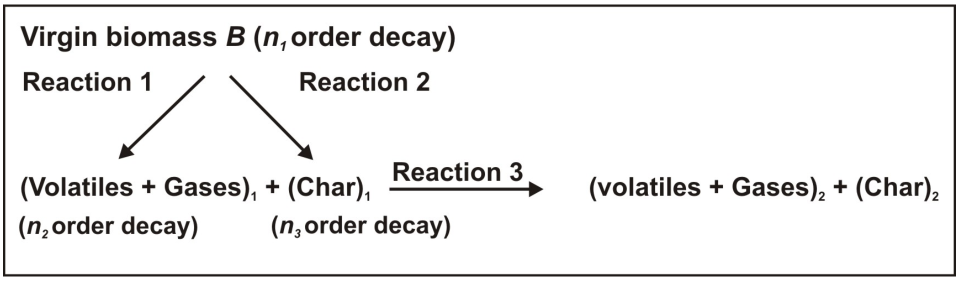

Figure 6.6: A kinetic model for primary and secondary pyrolysis (Koufopanos et al, 1991)

the role of chemistry tends to be understood as being far more significant than in reality. The explanation for this difference can be simply understood. Suppose a small element of a particle is undergoing pyrolysis. Any disturbance to enhance the rate, say, through sudden increase in local temperature causes enhanced generation of volatiles that prevent ingress of heat due to what is termed “blocking effect” (see for instance, Mukunda, 2007) in which any enhanced flow from the wall or surface will enhance the gas phase zone thickness and consequently, reduce the thermal gradients near the surface and convective heat transfer to the surface. This will inevitably modulate the volatile generation rate. It is important to recognize that the conversion is truly an *aero-thermo-chemical* process.

6.4 The thermochemistry of gasification - later part

Once the volatiles are produced from the raw biomass through the primary and secondary reaction pathways, the gases react with the air provided for the gasification. These reactions occur in the gas phase. The products of these reactions react also with the hot char crucial to “good” gasification. These reactions are defined below.

Gasification
$C(s) + O_2 \rightarrow CO_2 \quad H_r = - 393.5$ kJ (exothermic)

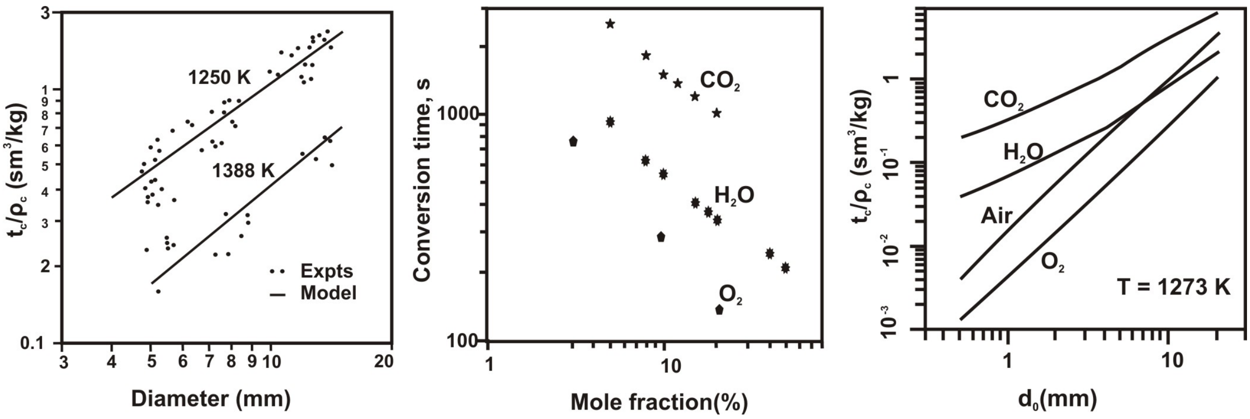

Figure 6.7: The conversion of char spheres with reactants: Left:Conversion time scaled with char density with char sphere diameter at 1250 and 1388 K: Middle: the char conversion time with the mole fraction of the reactant, the diluent being nitrogen; Right: The conversion time scaled with initial char density for various reactants with char diameter at 1273 K

$C(s) + H_2O \rightarrow CO + H_2$ H_r = + 131.3 kJ (endothermic)
$C(s) + CO_2 \rightarrow 2CO$ H_r = + 172.4 kJ
Partial oxidation
$C(s) + 0.5\ O_2 \rightarrow CO +$ H_r = - 110.5 kJ
Water-gas shift reaction
$CO + H_2O \rightleftharpoons CO_2 + H_2$ H_r = -/+ 41.1 kJ
Methanation
$C(s) + 2H_2 \rightarrow CH_4$ H_r = -74.8 kJ

In the reactions listed, H_r represents the heat of reaction and is the negative of heat of combustion. The principal gasification reactions, namely the reaction of C by H_2O and CO_2 are very important. The methanation reaction is the slowest because it needs two molecules of hydrogen to come together at the surface of carbon for the reaction to proceed. All the reactions excepting the water gas shift reaction are heterogeneous reactions. The mechanism of the reactions involves adsorption of the molecules on "active" centers on the surface, the actual atom exchanges on the surface and then the desorption of the species from the surface. The description of reaction mechanism is complex and a mathematical modeling of the process for gasification has been presented by Dasappa et al (1998).

6.5 Char conversion with O_2 (air), H_2O, CO_2

The combustion behavior of biomass (spheres, in particular) in an atmosphere of air has been examined in Chapter 4. The gasification process is largely a reaction between char and H_2 and CO_2. When air is introduced in the lower stages the reaction that occurs first is of char with oxygen in air. Thus it is of value to understand this reactive behavior. While the reaction of char with ambient air occurs with the char at high temperature $>$ 700°C, the reaction of char with H_2O and CO_2 can only occur at high temperatures. Also reaction with air is exothermic, but that with H_2O and CO_2 are endothermic. Thus after the reactions occur with air that raise the temperature of the gas and the char, the reduction reactions explained in section 6.4 take place leading to the final products of gasification. To obtain the information on the conversion rates with these gases Dasappa et al (1998) conducted experiments of char spheres in a high temperature furnace and monitored the weight loss with time in various atmospheres. A part of the data are set out in Fig. 6.7. The conversion times with O_2, air, H_2O and CO_2 at 1273 K are 10, 30, 40 and 300 s respectively. These show a curious feature that the conversion time with air and H_2O are about same at high temperatures. The reason is that the exothermicity of air and the endothermicity of H_2O reactions at high temperatures are not vastly different. It is not so with CO_2. It is the least reactive of all the reactants. The data in these plots are condensed into correlations as follows

$$\left[\frac{t_c}{\rho_c}\right]_{O_2} = 0.0022 d_0^2 X_{O_2}^{-1.0} \tag{6.1}$$

$$\left[\frac{t_c}{\rho_c}\right]_{CO_2} = d_0^{1.05} \exp\left[-1.715 + 35300(\frac{1}{T} - \frac{1}{1273})\right] X_{CO_2}^{-0.65} \tag{6.2}$$

$$\left[\frac{t_c}{\rho_c}\right]_{H_2O} = d_0^{T/1050} \exp\left[-3.26 + 15470(\frac{1}{T} - \frac{1}{1273})\right] X_{H_2O}^{-0.70} \tag{6.3}$$

In the above equations, t_c is the conversion time in s, ρ_c is the char density in kg/m^3, d_0 is the diameter in mm, X_i is the mole fraction of the species and T is the ambient temperature, the data being valid for $d_0 > 4$ mm. A typical value of ρ_c in the experiments was 200 kg/m^3.

The expressions are very revealing. The exponent of d_0 is 2 for oxygen. It is also around 1.85 for air. These imply that char – air reaction is diffusion limited (and also with O_2). The reaction occurs at the surface and the oxygen fraction at the surface is 0. No reaction occurs inside the sphere; this means it is a shrinking core behavior.

With CO_2 and H_2O, the reaction has much lower exponents. This implies that kinetic control is also present. CO_2 or H_2O diffuse into the pores of the char and reaction occurs all through the sphere. If it was completely reaction controlled, the exponent would be 0 because diameter has no effect at all. But this is not so. Hence there is combined diffusion-reaction control.

6.6 Combining the early and later parts of gasification

The way the early and later parts are combined in a gasification system is to introduce air to cause the pyrolysis process and generate volatiles that burn up with air immediately around the biomass or downstream in an area where air supply is intense. Allow these gases to percolate through a hot bed of charcoal for the reactions of the later part to take over and generate the combustible gas. The heat for the char reactions is provided by the exothermic flaming pyrolysis. The reactions proceed at high rates at high temperature on the basis of rates indicated in the earlier section and decrease as temperature drops because of the endothermicity of the reactions. Below a certain temperature, the rate of reactions is so small that in an actual system it can be taken that the reactions have frozen. Typically, this temperature is about 750°C. This intrinsic thermo-chemical feature ensures good gas quality over arrange of air flow rates through a system, as long as there is enough char available for the conversion process. An important result is that the air-to-fuel ratio remains about the same also implying that the equivalence ratio at gasification is roughly constant (0.25 to 0.27). This air-to-fuel ratio varies between 1.6 to 1.8 for downdraft systems. The hot gas-to-biomass ratio is about 2.6 to 2.8. The hot gas has about 10% moisture (by volume) and the cooling-cleaning system drops off the moisture leading to gas-to-biomass ratio of 2.5 to 2.7. Classically, the gas-to-biomass ratio of 2.5 is a well known value. This value is obeyed well for closed top systems and it goes up to 2.7 perhaps due to more complete reactions (closer to equilibrium) in open top reburn systems.

It is instructive to examine the stoichiometric reactions. Firstly we consider the combustion reaction,

$$CH_{1.4}\,O_{0.74}\,N_{0.005} + 0.98\,(O_2 + 79/21\,N_2) \rightarrow CO_2 + 0.7\,H_2O + 3.69\,N_2,$$

If we calculate the air-to-biomass ratio it is 5.25. We now consider the gasification reaction.

$$CH_{1.4}\,O_{0.74}\,N_{0.005} + 0.337\,(O_2 + (79/21)\,N_2)$$
$$\rightarrow 0.57CO + 0.485H_2 + 0.028CH_4 + 0.343\,CO_2 + 0.157\,H_2O + 1.27\,N_2 + 0.028\,C$$
$$\rightarrow 2.857\,(0.2\,CO + 0.17\,H_2 + 0.01\,CH_4 + 0.12\,CO_2 + .055\,H_2O + 0.445\,N_2 + 0.01\,C)$$
$$\rightarrow 0.137\,H_2O + 0.028\,C + 2.7\,(0.211\,CO + 0.18\,H_2 + 0.0105\,CH_4 + 0.1275\,CO_2 + 0.02\,H_2O + 0.471\,N_2)$$

The composition presented above follows closely what is practically real. The last equation is set in a manner to show the gas composition of the cooled gas. All the water above the equilibrium level of vapor at ambient temperature drops off in the cooling system. The air-to-biomass ratio for this reaction is 1.83. The cooled gas to biomass ratio is 2.7. If we now find how much of air is needed to burn this gas it will be (5.25 - 1.83)/2.7 = 1.26. Thus the air required to burn the gas is 1.26 times the gas flow rate (by mass). The molecular weight of the gas is 25.6 and that of air is 29. Thus it is 90% as dense as air. Of course, slightly different compositions will have slightly different densities.

If the open top reburn system is operated by closing the side air nozzles, the conversion of the volatiles is not adequate and char will be left behind. This leads to air-to-biomass ratios close 1.1 – 1.2 and hot gas-to-biomass ratios of 2.1 – 2.2.

6.7 Approaches to the gasification process

There are three broad ways in which the gasification can be arranged: fixed bed updraft, fixed bed downdraft and bubbling and circulating fluid bed systems (there are other sub-schemes like cross-draft fixed and entrained fluid bed systems which are variations of these). The basic aspects have been discussed in a number of earlier books and documents (Reed and Das, 1988; Reed and Gaur, 2000; Team, 2003; Rezaiyan and Cheremisinof, 2005; Knoef, 2005). It is important to appreciate the principles. The schematics of the principal systems is shown in Fig. 6.8.

6.7.1 Updraft system

In the first variety (left in Fig. 6.8), because the start-up scheme would be built around a fire-on-grate over which the fuel bed rests, the hottest zone is created over the grate because of the exothermic reaction of air with char and biomass. This zone extends over a few particle depths through which all the oxygen will get consumed. The products of combustion will percolate through the bed, heating up the biomass till volatiles are expelled from it. These volatiles are at temperatures of 300 to 400°C. The gases with a mix of product gases and volatiles will move further in the bed transferring heat to dry the biomass till both temperatures are nearly same. By proper feeding process, this temperature can be maintained at 150 to 200°C to ensure that the volatiles do not condense inside the reactor. The final product gas is composed of significant moisture, volatiles and product gases. The volatiles may condense into a viscous fluid. This is *tar* whose magnitude can go up to 100 g/m^3. This “tar” has components that are near-virgin volatiles processed thermally very little. In these systems the bed temperature is the highest around the bottom zone and decreases as one proceeds towards the exit. Europe, Finland

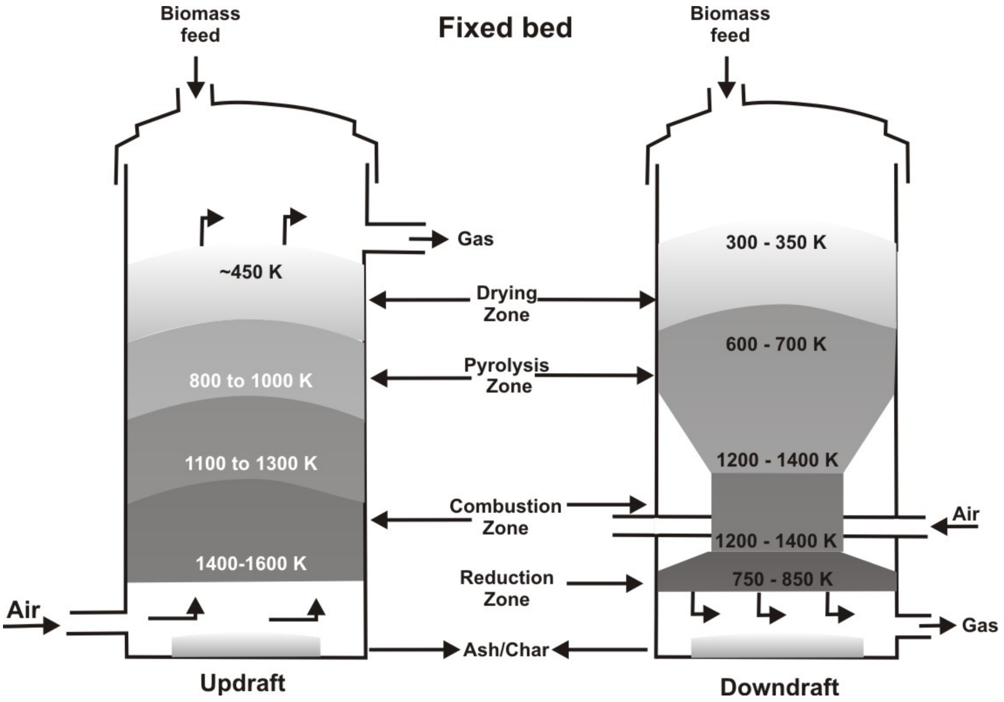

Figure 6.8: Schematics of an updraft, downdraft fixed bed as well as fluid bed and circulating fluid bed gasification systems

in particular has developed large updraft systems for district heating applications involving steam raising and steam power generation. It is favoured since it can accept a wide range of feed stocks that do not need significant preparation. The gas produced from such reactors are connected to boilers in very close proximity to avoid tar deposition issues.

6.7.2 Downdraft system

In the second variety, namely, fixed bed downdraft, there are three broad approaches - closed-top, open-top and staged-air-entry open-top systems. Of these, the closed top systems are in vogue from the time of World war II. The open-top systems were built initially for rice husk by Chinese [developed in 1976 or thereabouts, see Mendis et al, 1989 for details] and subsequently researched for other agricultural wastes [Kaupp and Goss, 1981; Kaupp, 1984] and biomass [Reed and others, 1982, 1988] and the staged air-entry open top systems researched and developed into modern technology in more recent times [Mukunda et al, 1993]. There are definite differences between these systems and it is important to appreciate them. The right hand side of Fig. 6.8 shows the downdraft system of the closed-top type. Air is drawn from the tuyeres arranged around the periphery to enter a zone below the fuel storage section. Sometimes, the storage section is enlarged in size to store enough fuel for 6 - 10 hours of operation. The air comes via nozzles at reasonably high velocities – 5 - 30 m/s, the high velocity being chosen to enable penetration into the core region in larger size reactors. Imbert class of close-top reactors employ velocities in the range of 20 to 30 m/s. Below the air nozzle, space is provided up to a zone where the gas flow is designed to pass through a constriction, called *throat*. This ensures that the hot gas gets mixed sufficiently with the air and passes through the throat region in the porous bed. The high velocities ensure high temperatures (see later) and the small zone of passage ensures adequate mixing to cause cracking of “tars” to small fragments. This process is effective at nominal operating conditions. This thermochemical process is effective with wood pieces with little ash and certainly ash with little potassium and low ash melting inorganic components. The reactor is operated by loading with charcoal to start with (for the first time) and then loading biomass periodically as it gets consumed. The biomass loses volatiles because of heat from the combustion zone and occasional recirculating air flow. This char then moves down due to the fact that downstream the char is getting consumed by the gasification reactions. The char then reacts with the air flow along with the volatiles generated in the zone above. The product gases flow downstream through the throat region by which time the char would have reduced in size (a) due to reaction with oxygen in the air and (b) fragmentation that occurs because of load from above and internal thermal stresses. The enhanced surface area along with high temperatures allows the reduction reactions of the char with carbon dioxide and water vapor leading to the generation of producer gas. Finally, char 3 to 5 % will remain back along with ash for final disposal. This gas that is drawn out from the reactor is cooled and cleaned of tar and particulates to yield a gas with a nominal cold gas composition of 17 - 19 % of CO, 15 - 18 % of H_2, CH_4 of 1 %, CO_2 of 12 %, H_2O of 2 % and the rest N_2. When the throughput comes down in the same system, the entire process - with low air velocities through the air inlets, lower temperatures in the reaction zone and possible reduction in mixing of streams will all lead to increased "tar" generation from the reactor. Further, if one uses biomass different from wood, particularly agricultural residues, there is a possibility that the residues have a fair amount of potassium that comes from fertilizers that are provided for better crop productivity. The presence of potassium reduces the ash fusion point and the entire packed bed might get fused. Of course, this can happen with even wood chips due to pick-up of mud, sand and grit from the soil if care is not taken to use clean biomass. Further, if wood with higher moisture fraction is used in the reactor, the entire temperature distribution will move to lower levels and inevitably, the tar generation will become more signficant. Thus, the off-design conditions, characterized by higher moisture-in-biomass, ash-fusion causing inorganic fraction and lower than nominal through-put can cause performance degradation in terms of gas cal value, operability of the system on a continuous basis and "higher" tar levels than acceptable. One can characterize the reactor design as better by one that is tolerant to the deviations from nominal operating conditions in providing steady performance consistent with thermodynamics. Downdraft systems can give gasification efficiencies up to 80 % and tar levels *lower than 200 mg/nm*^{3} *in the raw gas* from the reactor. The particulate matter generation and tar generation have *opposing trends with superficial velocity*. Low superficial velocities reduce the particulates but encourage tar generation and high superficial velocities do the other way. The levels of tar from the downdraft systems are the lowest compared to any other system. Further reduction in the tar generation occurs in the open-top reburn systems (discussed below).

6.7.3 Open-top fixed bed system for rice husk

Open-top systems were first developed in China for handling rice husk. Much of the early history of the technical part of this development is unknown. A brief description is found in Stassen (1995) and Bhattacharya (2001). What the Chinese have done is truly original and creditable even assuming that the groups there had access to European knowledge base on gasification, The reactor is a vertical cylindrical container into which rice husk gets loaded at the top. Air is drawn from the top and the reaction zone gets located much above the grate and can vary in position because of bed movements. The char/ash will drop into a water seal from which these are drawn out and disposed. The gasification efficiency (the ratio of the energy in the gas to that in the feed stock) is claimed to be 60 to 65 %. The gas that comes out of the reactor has to be cleaned of tar and dust before making the gas suitable for operation in engines. In fact the particulate and tar cleaning is very extensive and uses significant amount

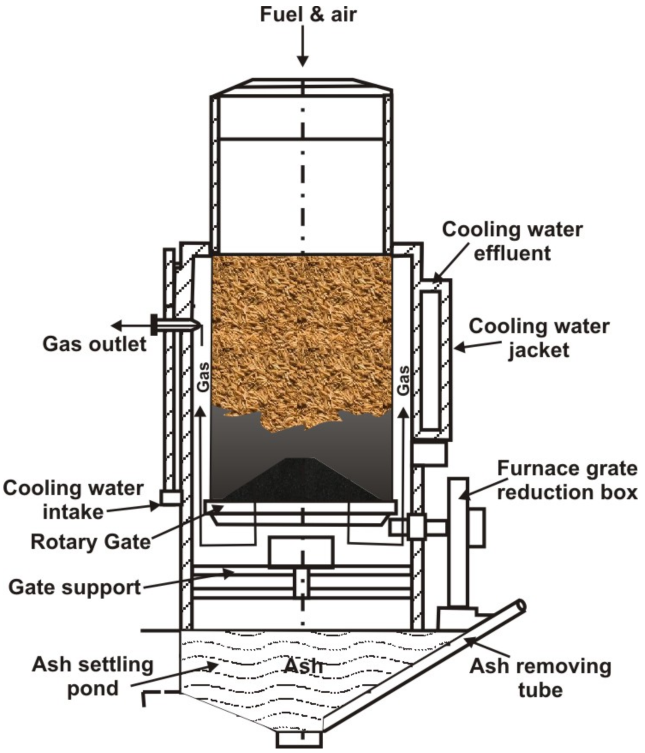

Figure 6.9: Schematics of the Chinese open-top downdraft fixed bed gasification system

of water. Recycling the water is not a part of the original design.

Since rice husk is very light (∼ 100 kg/m^3) and has significant ash that prevents char conversion (nearly), the volume reduction of the bed after de-volatilization is small and large reactor volumes are needed to handle rice husk for gasification. The volatile generation process (and the associated flame called flaming pyrolysis) is quite fast (a single particle completes it in about 1 to 1.5 s). The time required for the conversion of the carbon in the char however is very large - requiring about 100 s in an atmosphere of air, and 300 to 500 s in an atmosphere of CO_2 and H_2O at temperatures of 700 - 800°C. However, in a packed bed of the gasification system, the conversion of char is nearly not possible. In fact, fluidized bed *combustion* systems using rice husk working at 800 to 850°C can convert only half the carbon in the char (we should note that rice husk has 60 % volatiles, 20 % carbon and 20 % ash). Consequently, nearly no carbon gets converted in a gasification system that uses as-received rice husk. It will be brought out later that more than 80 % of the residual carbon can be converted into gas when rice husk is briquetted into solid blocks 30 to 70 mm in size in the open-top reburn class of gasification system (the system developed at the Indian Institute of Science).

One of the serious issues with such fixed beds with light biomass like rice husk is that the flow of gases over the cross section is not always uniform, Occasional slumping in one part that cannot be avoided can reduce the resistance along that path and more air flows through that zone. This makes a part of the reaction process less fuel rich and other parts more fuel rich. This leads to greater tar generation. Providing mechanical slow agitation does help in part. These imply that the gas generation process and quality vary significantly over the operational time. Use of a gas holder some times offsets the gas flow rate and compositional variations. Many crop residue based gasification systems in China have a large gas holder to act as a buffer between the gasification system and the power generation system to decouple the two processes. Apart from these aspects, the cooling water carries a heavy load of tars, phenols and fine particulate matter, treatment of which is very expensive. However, because of the simplicity of the system and wide spread availability of rice husk in rural and semi-rural areas, the Chinese system has spread widely, efficiency and environmental compliance issues taking a backseat.

6.7.4 Fluidized bed systems

Fluidization systems have been described in section 4.13, particularly in Fig. 4.6. The primary difference between fluid bed gasification and fluid bed combustion systems is in the amount of air flow that can be passed through the bed. It should be typically a third of that for combustion. It is not entirely easy to match the flow rates for gasification. And the throughput of "tars" from the system are so large needing a separate tar-cracker that it is not economical to build fluid bed gasification systems at small throughputs. However, when it comes to large throughputs, both process and system size considerations favour circulating fluid bed gasification systems. Such systems will need a separate tar cracking system if the gas has to be used in an engine (gas turbine, mostly). The tar fraction in these systems will be typically, 1 to 3 g/nm^3 composed mostly of primary and secondary fragments. Tar reduction is performed in catalytic tar crackers, the catalytic bed being made of high surface nickel and some noble metals at temperatures of 1000°C. To maintain the temperature, the gas is burnt sometimes with a small amount of air inside the catalytic bed. These elements are usually expensive and are meaningful for adoption at high throughputs.

The tar generation values are way above the values for tar generation in downdraft gasification systems. For small power systems - by which is meant a throughput less than 2 t/h of dry biomass (up to 2.4 MWe) - a fixed bed downdraft reactor turns out to be more appropriate instead of fluid bed as the overload in terms of tar cracking systems is not demanded. Many systems in Europe and the USA are at large throughputs - up to 20 t/h use circulating fluid bed systems. The particulate generation is also significant and therefore, the gas clean-up systems need to be elaborate.

6.7.5 Open-top re-burn fixed bed system

This reactor system is unique to the development at Indian Institute of Science (IISc) that took place in 1984-1985. It combined the work on the modification to reactors with throat that was being conducted from 1982 to ideas from the work of Reed and Markson (1982, 1983). While the reactor contemplated by Reed and Markson is like the reversed Chinese open top configuration, but meant for wood chips, the system evolved at IISc has staged air entry - at the top as well as the sides at one or more locations on the reactor. Figure 6.10 shows the cross-section of the reactor. The developments of the elements even on the integrated version have taken place over a period of time. What is shown is the current configuration. It has very little resemblance to the classical closed top. The idea of storing biomass for a specific period of operation is abandoned in favor of having a volume that allows a steady operation with periodic loading of the biomass chips from the open top. The reaction zone occurs in the simple cylindrical chambers with ceramic inside ensuring long reactor life and better insulation. The ash and char are extracted by using a screw at the bottom. This replaces a rotating grate in a classical closed top design that was found inadequate for positive extraction of char/ash if one had to use biomass of higher ash content (like rice husk briquettes for instance) or when some amount of ash fusion has occurred in the reactor due to pick-up of inorganics in the biomass.

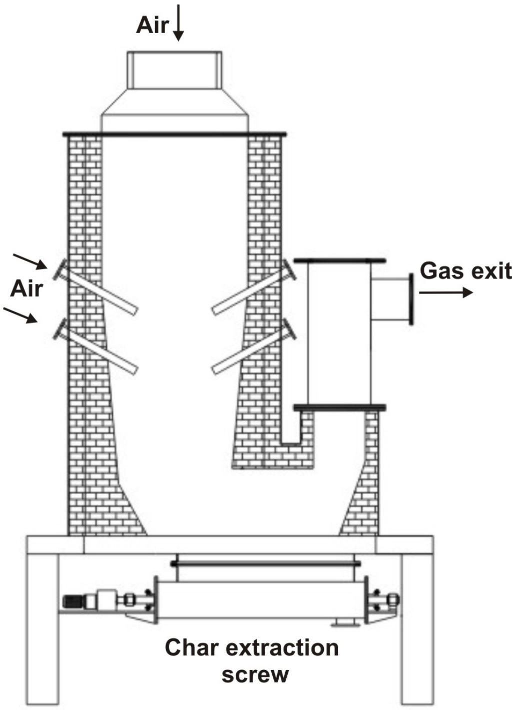

Figure 6.10: The cross section of IISc reactor design. Note the open top, two sets of side air nozzles and a screw ash extraction system

The single most important aspect of this design is the possibility of using wide range of fuels - wood pieces with smaller size, coconut shells that have high surface area per unit mass and biomass and agro-residue briquettes with ash having potassium like Ipomia (a weed with ash having nearly 50 % potassium), sugarcane trash, pine needles, and even urban solid waste. Since the reactor is designed for solid biomass, it is expected that any kind of biomass irrespective of shape or size should be dried, pulverized and briquetted or pelleted before use in the reactor as long as the biomass is not solid like corncobs, coconut shells or wood. While corncobs can be used directly after drying, if needed, Coconut shells are to be broken to pieces and wood poles should be sized. The multi-fuel capability that *enables high conversion efficiency without ash fusion is obtained because of air-flow distribution*. Classical closed top design has air entry nozzles only at one height and the velocities through these nozzles are high $\sim$ 10 to 30 m/s. The peak bed temperatures are measured in the air nozzle area and set out in Kaupp and Goss (1981). These data of different air nozzle diameters from 3.2 to 19 mm with air velocities from 10 to 100 m/s can be condensed into a single plot of the peak temperature as a function of Reynolds number ($\rho u d_n/\mu$) as seen in Fig. 6.11. The bed temperature increases from around 1000 K to as high as 1800 K. The ash fusion temperatures are in the range of 1100 to 1300 K. Hence it is clear that the air velocities need to be restricted to ensure that ash fusion does not occur. Combining the ability to prevent ash fusion while maintaining a minimum temperature to encourage tar cracking for minimizing the tar in the gas stream at desired turn-down ratios (nominal to a minimum throughput) is nearly not possible in a closed top reactor.

By arranging the air flow from the top as well as the sides as in this design, the effective superficial velocity at one cross section is brought down significantly ($\sim$ 0.10 to 0.2 m/s). The flow rate from the top is about 50 to 70 % of the total flow rate. This flow acquires relative uniformity over the cross section in a few particle depths except at the outer periphery where the porosity is larger than in the core region. The reactor can be operated with side air nozzles

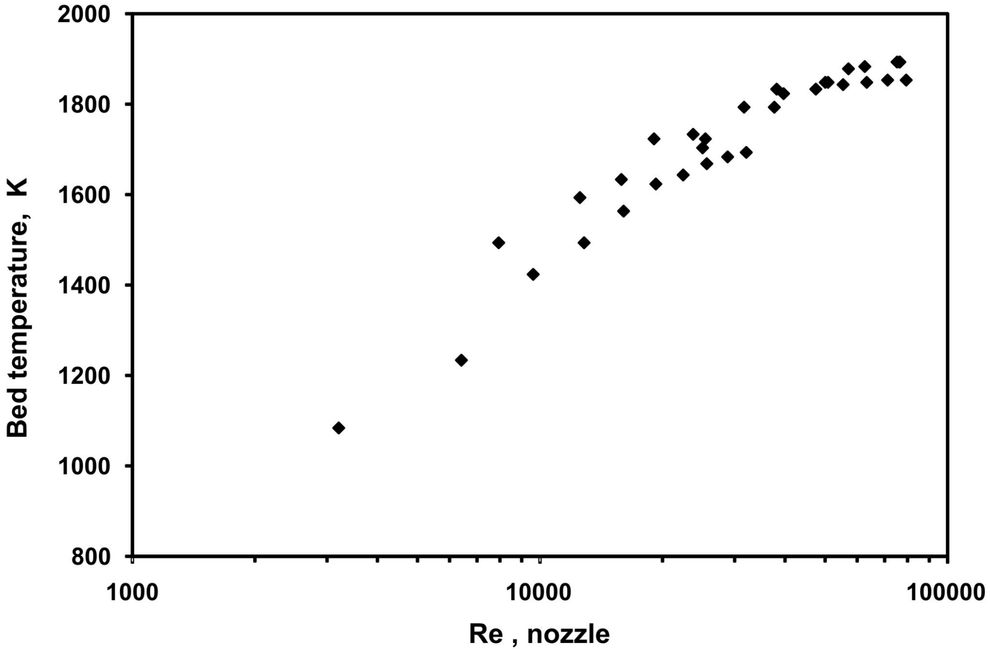

Figure 6.11: Bed temperature as a function of Reynolds number of the air jet reflecting the influence of nozzle diameter and air velocity. The data are for nozzle diamters are 3.2, 7.9,12.5, 19 and 24 mm and velocities from 10 to 100 m/s

closed or the top region closed. To appreciate the differences, the results from tests with side air nozzles closed as well as open are set out in Fig. 6.12.

The case of side air nozzle closed

If the air nozzles are closed (right side figure) and the reactor is operated in a mode that is identical to what was conceived by Reed and Markson (1982, 1983). To begin operations in this mode, the reactor is loaded with charcoal to a position much above the side air nozzle and over that biomass is loaded and the start-up is done by lighting the charcoal through the side air nozzles with a separate torch. Once the system light-up has occurred, the side air nozzles are closed. From this condition onwards, the air flow is received only from the top. The hot particles in the bed at one layer will radiate heat through the spaces between the particles and this provides an ignition source for the incoming fuel. When the fresh fuel gets heated to a point that volatiles are generated, the volatiles mix with the incoming air and the mixture gets ignited in the high temperature environment. This combustion process is sub-stoichiometric and is rightly termed by Reed and Markson (1982) as flaming pyrolysis. The process of radiant heat transfer from one layer ⇒ heat-up of fuel pieces in the upstream layer ⇒ gaseous flame in the near-environment ⇒ ignition of the upstream layer. This process causes a propagation of the flame front upwards and is called stratification process (Reed and Markson, 1982). The flame keeps travelling upwards till the top layer is reached. The rate of upward propagation is *linearly dependent on the air flow rate* from the top. When the flame reaches the top, the entire bed becomes a charcoal bed and if the air flow is drawn through the reactor further, it will behave as a gasifier with hot charcoal.

If we use pieces of wood or coconut shell as the fuel, then the bed will reduce in volume because the mass loss will be close to 80 % and the volume reduction only about 25 %. Conse-

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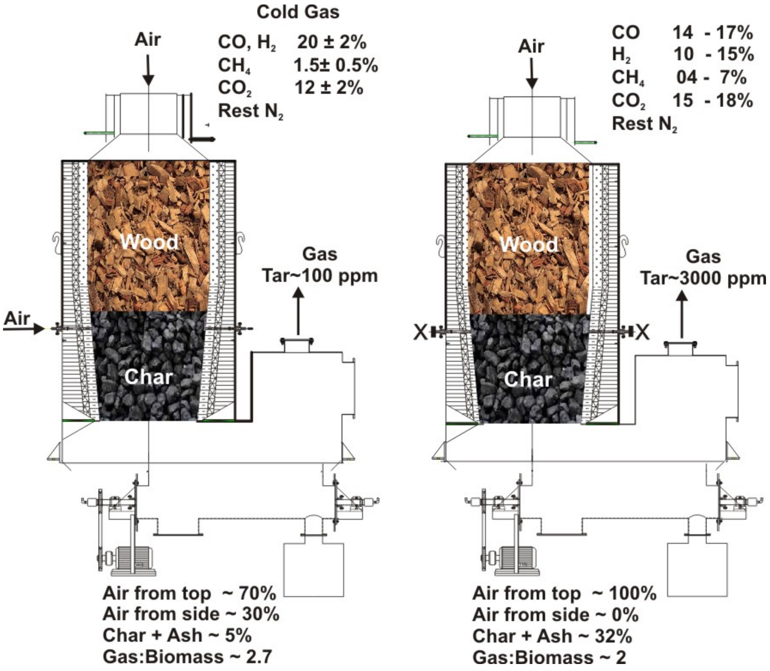

Figure 6.12: The results of IISc reactor with side air nozzles open and closed

quently, the volume of the entire bed will reduce to about 30 % of the original volume. On the other hand, one could continue topping up the fuel till the entire reactor is filled with charcoal. If steady operation is desired, one would need to extract the char, typically at 30 to 33 %. This operation then becomes a charcoal producer as well. The gas composition shown in the figure indicates that both CO and H_2 are lower than for the case of air nozzles open but CH_4 much larger. This clearly points to generation of significant amounts of tar as is indeed the case. The amount of tar from this operation will be close to 3000 mg/nm^3 (nearly same as 3000 ppm). The gas has a calorific value (with the tars) of 5.2 ± 0.2 MJ/nm^3 and is suitable for being used in a boiler kept close to the gasification system. The exit temperature from the reactor is about 550°C and hence is such that the gas with the tars can easily be piped (with insulation) into the combustion chamber of the boiler without the fear of condensation. The operation of the system in this mode has been designed and built for activated charcoal generation with coconut shell as the fuel.

Side air nozzles open

When the side air nozzles are opened, the gasification process undergoes a drastic change. Because the flow rate from the top is reduced, the rate of propagation of the flame upwards gets reduced. Further, the air flow from the side will (a) burn with the gases generated from the flaming pyrolysis that raises the local temperature to levels much more than with air nozzles closed and (b) consume the char by part oxidation of the char, but more significantly from the endothermic reactions with CO_2 and H_2O. This causes the consumption of the bed char unlike the case with air nozzles closed. The combination of reduced upward propagation rate and the char consumption below the air nozzles stabilizes the flaming pyrolysis zone in a range about 100 to 300 mm above the air nozzles. This approach to re-burn of the volatiles with side air nozzles and the char reaction is expected to provide lesser tar. This can be appreciated in a comparative bed temperature with height in closed-top and open top systems (Mukunda et al,

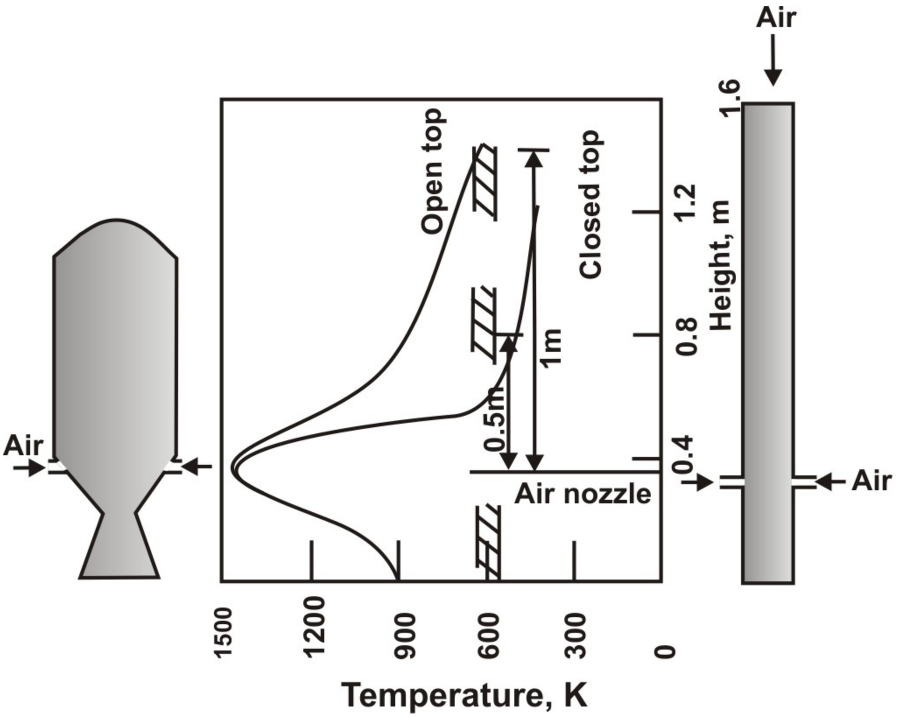

Figure 6.13: Bed temperature with height measured in closed top and open top systems drawn from Mukunda et al, 1993

1993) as in Fig. 6.13. The temperature decrease with height in closed-top systems occurs faster than in open top systems. The phenomenon dominating the upper portion of closed-top systems is largely pyrolysis, but that above the side air nozzles in the open top system is oxidative pyrolysis (or flaming pyrolysis). The oxidative pyrolysis keeps the temperature higher than in closed top systems. At the same throughput, the overall temperature profile is much better in the case of open top compared to closed top systems. Now as the throughput goes down, the temperature profiles become weaker; this is compensated by broader profile that enhances the residence time and hence maintains better tar reduction ability. An important element in the whole process is the ability of chars to crack the tars on which explicit evidence has been provided by Kaupp (1984). In an elegant and simple set of experiments on an apparatus shown in Fig. 6.14, tar is injected into a tube (a) maintained empty and (b) filled with char with the entire apparatus kept inside a furnace at high temperatures (680, 800 and 920°C). The extent of cracking is measured downstream by analyzing the product sample. These show that even while high temperature cracks tar, the passage through char enhances cracking clearly by as much as 25 to 35% in addition. Thus maintaining a higher temperature char bed is important for tar reduction and it is suggested that this is key to the better performance of the open-top re-burn systems.

We will return to further discussion on gas quality in subsequent sections.

6.8 Flame propagation through packed beds

Figure 6.15 shows the three configurations by which the sized biomass pieces or charcoal can be arranged for causing the thermochemical conversion. Of these, the most pertinent for operations to produce clean gas is the last one - (c), the bottom lit staged air injection downdraft

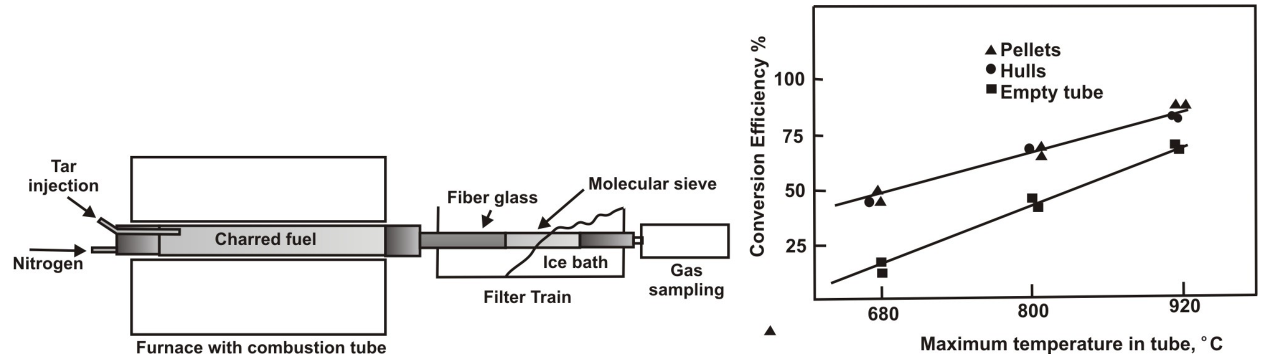

Figure 6.14: The experiment on the extent of cracking in a hot char bed, from Kaupp, 1984

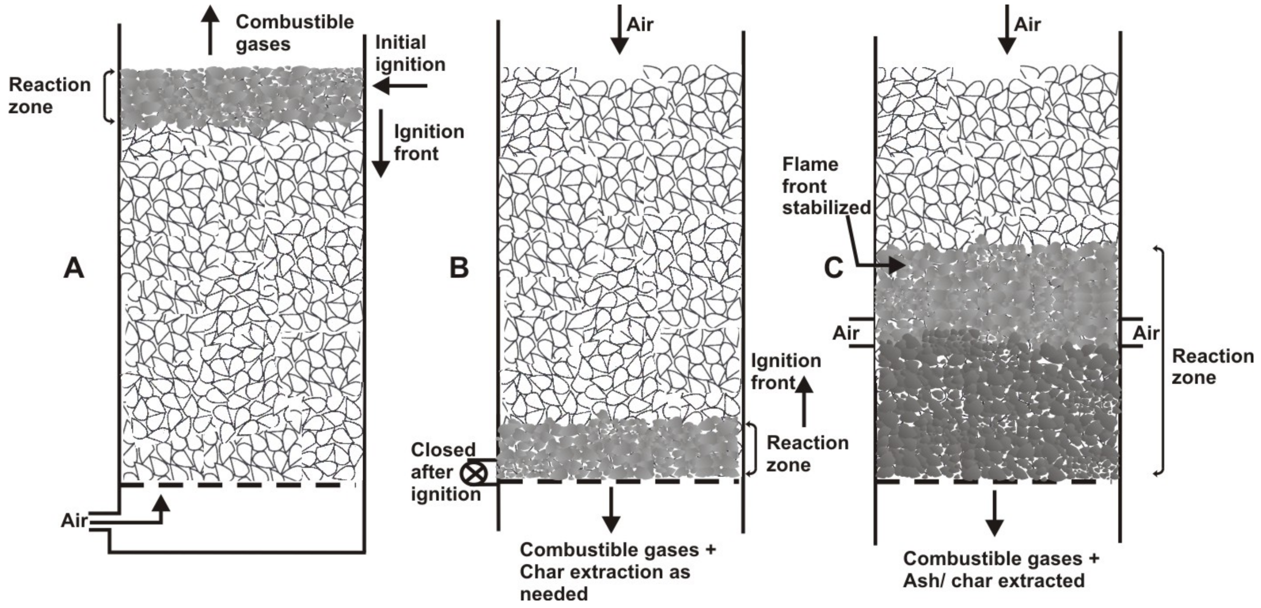

Figure 6.15: The three types of flame propagation in beds - Left: Top-lit updraft, Middle: Bottom lit downdraft Right: Staged air-entry system lit through the side air nozzles with air nozzles open

system. The middle configuration (b) in which air nozzles are closed after lighting the system via these ports is called bottom lit downdraft system, the one meant for charcoal generation and extraction. The first configuration (a) is called the reverse downdraft system or top lit updraft system. The simplest of the configurations where the processes are easily understood is the configuration (a). In all the cases, there is a fundamental behavior of flame propagating against the stream of air flow through the bed (once initiated or ignited). The propagation rate in the above cases can be measured as the rate of movement of the bed over a certain time along with mass loss and/or of a thermal profile tracked by introducing thermocouples at various heights; the temperature vs. time from these thermocouples is analyzed to see how long after is a downstream station at a fixed distance acquiring a fixed high temperature (say, 600°C). If we measure the air flow rate into the bottom or the top region in the first two cases and also measure the mass burnt over the burn duration, one can obtain the air-to-fuel ratio. It is important to capture the important features and differences amongst these modes of flame propagation.

When the biomass layer is lit at the top with air passing upwards as in the case top-lit updraft system, the bed and the flame front move against the flow (implying downward direction) together at a speed $\dot{r}$ measured by the procedures discussed above. As the operation is continued, the bed and the flame come downwards till the flame front reaches the grate at the bottom. Depending on the flow rate it may turn out that the hottest zone is located within the char bed with cooler char layer above the flame front. After the flaming period, the biomass bed slumps into a hot char bed. From the moment the entire char bed gets formed, air meets with the hot char at the bottom and hence oxidises the char. At this stage, the propagation occurs from bottom to the top converting the entire char finally into a bed of ash. Thus the char conversion occurs in a co-flow mode - with air flow and front propagation occurring in the same direction.

In the bottom-lit downdraft case (middle one in Fig. 6.15), the flame travels upwards against the flow exactly as in the above case (and hence in an upward direction). With reference to a biomass particle ahead of the flame front, the thermo-chemical behavior of the propagating front is identical both the cases. However, when referred to a fixed coordinate system like the grate, the dynamics is very different. As different from the top-lit case, the hot gases pass through a hot bed of char accumulating over the grate; the propagation rate will be affected by the conversion of char due to the passage of hot gases from the flame zone. The propagation rates will have the same qualitative behavior of increasing with increased superficial velocity, V_{sup} (typically 3 - 7 cm/s) until a stage in which the residual char after flaming is nearly constant. In this regime, the flame will propagate to the top converting all biomass to char. Then the reactor becomes a hot char bed downdraft gasifier. Beyond this stage, the behavior is the same as in the earlier case after the char bed is developed.

At larger V_{sup} of 7 to 40 cm/s, the amount of char left behind starts dropping and the propagation rate also drops from a maximum till comes a stage when nearly all the char will be consumed due to reactions of hot char with O_2 in air in the top-lit case and due to reactions of hot char with H_2O and CO_2 in the bottom-lit case. The nature of the variation of the propagation velocity with V_{sup} will be different in the two cases.

In the staged air entry case (the right-most in Fig. 6.15), the air entry from the top will be lower than in the middle case as part of the air enters from the side nozzles. There are therefore three effects - (i) reduced propagation rate compared to the middle case at the same total air flow rate, (ii) reduction in volume due to conversion of biomass to char due to significant volatile mass loss (about 80% up to some total flow), and (iii) char consumption (both oxidation and reduction) due to side air entry. These processes under certain divisions of flow from the top and the sides (typically 60 to 70% from the top) limit the propagation rate to an extent that for all practical purposes, the bed can be considered stable at some height from the side air nozzles as shown in the figure.

Several studies have been made on the top-lit configuration by Saastamoinen et al (2000), Ronnback et al (2001), Horttanainen et al (2002) and Thunman and Leckner (2005). They address primarily the gasification regime for combustion applications that arises when a thin bed of pellets moves on a travelling grate. The broad behavior described in the earlier paragraphs is illustrated with data from Ronnback et al (2001) as well as Varun (2010) in Fig. 6.16 as $\rho_p \dot{r}$ and peak temperature (T_{max}) vs. V_{sup} for several cases discussed earlier. The air-to-fuel ratio and the char left behind after the flaming combustion phase obtained from the experiments for the top-lit case is shown in Fig. 6.17. The data is composed from several sources noted above and some from the laboratory (Varun, 2010). The figures contain a wealth of information hitherto unexamined in the literature. The use of $\rho_p \dot{r}$ accounts for the effect of the density of pellets because the surface heat balance relations are always in terms of surface mass flux. It appears that this feature is still to be appreciated as seen from the recent papers (see for instance, Harttanainen et al, 2002). The data of biomass pieces of different densities plot on to the same curve as also shown in Ronnback et al (2001). For wood chips of a density of 500 kg/m^3, the

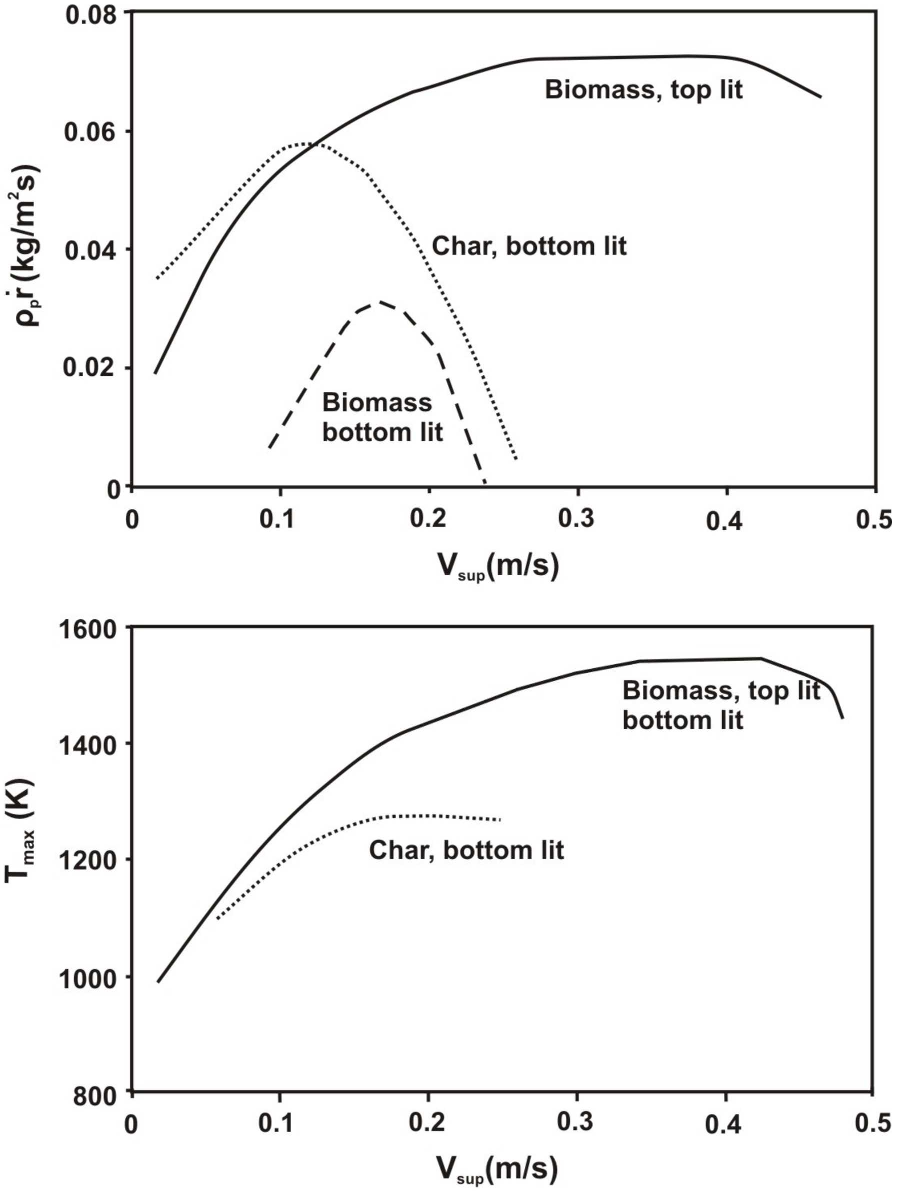

Figure 6.16: The flame propagation rate and bed temperature with superficial velocity for wood and pellets

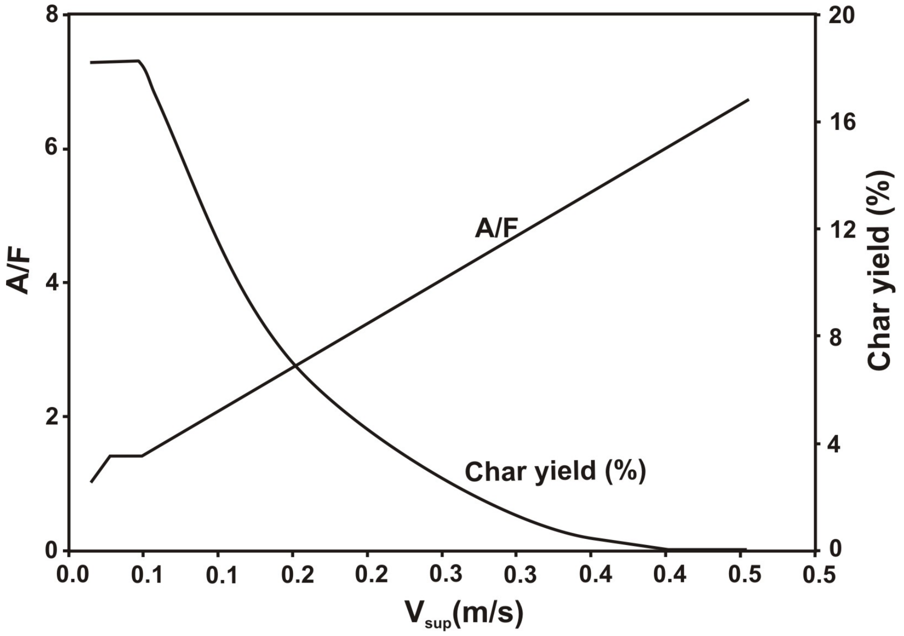

Figure 6.17: The air-to-fuel ratio and char yield with superficial velocity for wood and pellets for the top-lit case

peak propagation velocities are 500 mm/h for biomass top-lit case, 430 mm/h for char bottom-lit case and 220 mm/h for biomass bottom-lit case.

The value of V_{sup} used in top-lit designs is of the order of or less than 0.05 m/s to reduce the emission of particulate matter in the combustion gases. In this range the fuel mass flow rate varies linearly with air flow rate keeping the air-to-fuel ratio constant at 1.5, as seen in Fig. 6.17. The behavior of peak bed temperature, T_{max} with V_{sup} follows the broad behavior of the propagation rate. The increase of T_{max} with V_{sup} occurs even in the regime (V_{sup} up to 6 cm/s) where the overall air-to-fuel ratio remains the same. The bed temperatures with pellets are higher than with wood chips. We must appreciate that the reported measurements of bed temperature with thermocouples occurs in an environment of the thermocouple bead surrounded by hot char particles all of which are radiating to the bead and a gaseous flame in the space between the particles. There is also a flow around it that should lead to an estimate of the temperature of the hot gases. The thermocouple actually provides an output that is weighted mean of the two effects. It can be taken that the measured value is heavily weighted in favor of the char temperature as the radiation in the confined space dominates the heat transfer. In this regime, the presence of ash layer significantly influences the conversion process as has also been recognized by Cooper and Hallet (2000). It is pertinent to note that the peak bed temperatures achieved here (1550 K at estimated Reynolds numbers of 200) are lower than the peak bed temperatures in the closed top gasification system with air nozzles (1900 K) as shown in Fig. 6.11. This difference is primarily due to the fact that that at the high velocities in the air nozzles (up to 30 m/s leading to Re $\sim$ 80,000) that causes the ash layer to be blown away leading to the exposure of fresh char surface continuously.

There are two aspects of the observed behavior, namely, T_{max} increasing with V_{sup} even while air-to-fuel ratio remains constant over some range of V_{sup} and remaining nearly constant over a broad air-to-fuel range obtained over V_{sup} values of 0.2 to 0.4 m/s that need explanation; it lies in the role of ash build-up on the surface of the char. The processes that occur inside the packed bed are shown in Fig. 6.18. Increased V_{sup} implies increased local velocities in the space between particles and hence increased heat and mass transfer to the surface of the particles. This will inevitably increase the surface temperatures and increased conversion rates. The amount converted in the low V_{sup} range appears to largely balance the air flow rate leading to a constancy of air-to-fuel ratio even as T_{max} keeps increasing. As the particle is converted to gases ash keeps building in regions where the conversion has taken place. In the oxidation regime, this occurs in a shrinking core manner. In the gasification regime that is dominated by reactions of char with H_2O and CO_2, the conversion occurs in part, in the interior as well because diffusion rates of the gases into the pores are comparable or larger compared to reaction rates. It has been demonstrated by Varun (2010) in single char sphere studies that it is it imperative to invoke the ash layer to explain the char conversion with air. In attempting to explain the burn rate behavior of single spheres particularly in the char mode it has been found that radiant heat transfer from the hot char sphere is important and this is so large if the surface does not have ash deposit on it one cannot explain the observed results. The heat and mass transfer is composed of convective transport from flowing gases and the transport through the ash layer. The ash layer becomes increasingly important from the moment it gets formed. With increased flow rates, the boundary layer becomes thinner and the ash layer dominates the transport process. This is the reason why with increased flow rates, the presence of the ash layer becomes more important and the measured temperatures and consumption rates reach saturation.

The char left behind after biomass loses volatiles is $\sim$ 20% in this regime. As V_{sup} increases, the propagation rate increases but air-to-fuel ratio also increases and the amount of char left behind after flaming keeps decreasing to zero when the air-to-fuel ratio reaches stoichiometry as seen in Fig. 6.17. The propagation rate reaches a peak and levels off till after the stoichiometric condition is reached and then drops off.

In the case of bottom-ignited downdraft propagation, as the flame travels upward, char is left behind the propagating front. The magnitude is similar to the ones just noted above since the thermochemistry of the propagating front is the same in both. There will be a change in volume because the biomass will shrink in the process of becoming char due to loss of volatiles. This reduction leads to reduced propagation speed referred to the grate. That is why the two curves are parallel with the bottom-lit case at a lower level (the dotted line in Fig. 6.16). However at V_{sup} of 0.15 m/s, the propagation rate reaches a peak and starts dropping off beyond this V_{sup} till 0.25 m/s at which stage the propagation ceases. The reason for this behavior is the char consumption due to oxygen in the bed. The oxygen in the air flow consumes *the volatiles generated* in sub-stoichiometric mode till V_{sup} = 0.15 m/s at which stage it reaches stoichiometry. Beyond this V_{sup}, there is more oxygen in the flow than is consumed by the volatiles. Beyond this point the air-to-fuel ratio with *volatiles* becomes *lean* (Varun, 2010). Hence, the residual hot oxygen in the stream will attack the char and consume it with increasing vigour till V_{sup} of 0.25 m/s. This is the reason that the char left behind keeps decreasing as shown in Fig. 6.17 for the top-lit case.

The behaviour of char bed in the bottom-lit mode is similar to the case of biomass bed but shows much higher propagation velocities than biomass. The reason for this is that the processes that occur in the char bed occur at higher temperatures than in the biomass bed and hence the rates are higher. Also the gas phase reaction rates are not as high as in the case of biomass. Hence oxygen is consumed over a longer bed length. These may be responsible for the shift in the value of V_{sup} at which peak in propagation rate is observed for char compared to biomass. Differences in the stoichiometric ratios for char and biomass also contribute to this behavior.

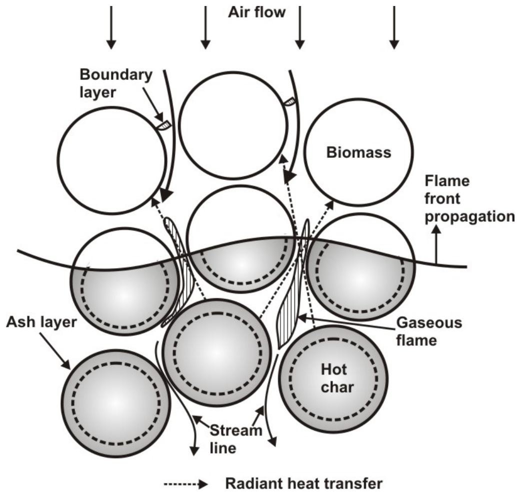

Figure 6.18: The processes that occur inside a packed bed leading to flame propagation

6.8.1 Model for flame propagation

The propagation of the flame occurs against the flow through the bed because the hot char bed transfers heat by radiation for the degree of visibility provided by the intervening spaces between the particles as shown in Fig. 6.18. The air flow through the bed causes convective cooling in the region ahead of the flame front. Increased air flow leads to increase of the heat transfer to the surface, enhanced generation of volatiles and higher heat release rates inside the bed. Also through the char bed, the temperature increases because of convective transport of the reactants – O_2 largely with exothermic reactions at the surface. The propagation rate can be taken to be controlled by the biomass reaching a temperature that releases volatiles which is typically $350 \pm 25°C$. For the sake of simple analysis, it is taken that the biomass pieces that are typically about 10 mm or less heat up uniformly. What this approximation implies is that the conduction time is small compared to propagation time. The heat balance can be written as

$$mc_p \frac{dT_p}{dt} = f_{view} \epsilon \sigma (T_f^4 - T_0^4) A_s - h_c (T_p - T_0) A_s \quad (6.4)$$

In words it is Particle heating rate = Radiant heat transfer to the particle - Convective heat loss rate.

This can also be represented as

$$\frac{m}{A_s} c_p \frac{dT_p}{dt} = f_{view} \epsilon \sigma (T_f^4 - T_0^4) - h_c (T_p - T_0) \quad (6.5)$$

so that we have a flux balance. In the term on the left hand side of the above equation, m is the mass of the particle = $\rho_p (\pi/6) d_p^3$, T_p is the particle temperature, f_{view} is the radiational view factor, ϵ is the surface emissivity, T_f is the effective flame temperature in the hot char bed, T_0 is the upstream biomass bed temperature, A_s is the area of the heat transfer surface, d_p is the diameter of the particle, ρ_p is the density of the particle and h_c is the heat transfer coefficient. Solution of this equation leads to

$$(T_p - T_0) = f_{view} \epsilon \sigma T_f^4 \left[1 - exp(-\frac{h_c A_s t}{m c_p}) \right] \quad (6.6)$$

In the radiation term, T_0^4 is dropped off as it is very small compared to T_f^4. The effect of the density of pellets expresses itself along with the regression rate, $\dot{r}$ because the surface heat balance relations are always in terms of surface mass flux. It appears that this feature is still to be appreciated as seen from the recent papers (see for instance, Harttanainen et al, 2002). By identifying the temperature, T_p to be attained at time, $t = t_p$ with the pyrolysis temperature, T_{pp}, we can evaluate the propagation rate from $\dot{r} = d_p/t_p$. We substitute $T_p = T_{pp}$ in the equation 6.6 and also set $t = t_p$ to get

$$t_p = \frac{mc_p}{A_s h_c} ln \frac{1}{1 - h_c(T_{pp} - T_0)/f\epsilon\sigma T_f^4} \tag{6.7}$$

We can obtain $\dot{r}$ as

$$\rho_p \dot{r} = \frac{6h_c}{c_p}\left[ln \frac{1}{1 - h_c(T_{pp} - T_0)/f\epsilon\sigma T_f^4}\right]^{-1} \tag{6.8}$$

The heat transfer coefficient, h_c is obtained from

$$h_c = \frac{k}{d_p} Nu = \frac{k}{d_p}(2 + 0.9Re^{0.5})\frac{Nu}{Nu_0} \tag{6.9}$$

The term in brackets is the Nusselt number for flow past bodies in a laminar flow and the ratio Nu/Nu_0 refers to blocking effect. It is particularly important for low mass flux from surfaces. It is expressed as $Nu/Nu_0 = ln[(1+B)/B]$ where B is called the transfer number (see Mukunda et al, 2007 for relevant discussion). B is defined by

$$B = \frac{H_c Y_{ox}}{c_p(T_p - T_0)} \tag{6.10}$$

where H_c is the heat of combustion of the reaction between oxygen diffusing to the surface and the carbon, Y_{ox} is the oxygen fraction of the stream. B is the ratio of the heat released by combustion to the sensible enthalpy. Its typical value for the present application is about 6 to 10, the variation being due to the variation in the heat of combustion. It varies from 10 to 18 MJ/kg depending on the ratio of CO_2 to CO formed at the surface. The variation of the term $ln(1 + B)/B$ is 0.35 to 0.25.

The Reynolds number Re is defined as $Re = \rho V_{sup} d_p/(\mu 1 - \epsilon_0)$ where μ is the viscosity of air, ϵ_0 is the porosity of the packed bed. For the range of Re of 20 to 700 for these systems, the exponent on Reynolds number is chosen anywhere between 0.4 to 0.6 (here it is taken as 0.5).

To see if the simple model described above will provide predictions that are meaningful, calculations have been made with typical parameters. The parameters chosen are d_p = 8 mm, μ = 1.2×10^{-5} kg/m s, f_{view} = 0.15, ϵ = 0.8, $\sigma = 5.678 \times 10^{-8}$ W/m$^2 K^4$, k = 0.017 W/m K, $T_{pp} - T_0$ = 380 K, Nu/Nu_0 is taken as 0.4 for a V_{sup} = 0.2 m/s and 0.3 for other cases. The results are shown in Table 6.1. In obtaining the propagation rate ($\rho_p \dot{r}$) as in the last column, the coefficient 6 in eqn 6.8 is replaced by 1. This amounts to just 16% of the surface being adequate for absorbing the heat. At present, there is no justification for this choice except that the actual values obtained are in the same range of observed values. The theory contains all the essential features for predicting the propagation rate. The results shown in the Table 6.1 use the experimental bed temperature data as the theory for predicting bed temperatures is more involved and is not presented here. The radiation term is the dominant quantity that drives the propagation rate. Convection is very important at the limiting ends – extinction at small and large V_{sup} values. At both the ends, temperature drops to such values that radiation barely balances the convection term. This leads to

$$V_{sup,crit} = \frac{\mu}{\rho d_p}\left[\frac{d_p}{k} f_{view}\epsilon\sigma T_f^4 - 2\right]^2 \tag{6.11}$$

Table 6.1: Propagation rate and bed temperatures as a function of superficial velocity, V_{sup}, Term1 = $f_{view}\epsilon\sigma T_f^4$, Term2 = $\frac{k}{d_p}$ (2 + 0.9 $Re^{0.5}$) Nu/Nu$_0$

V_{sup} m/s	T_f K	Re	Term1 kW/m^2	Term2 kW/m^2	Frac	$\rho_p \dot{r}$ kg/m^2 s
0.02	950	26.7	5.5	2.5	0.45	0.011
0.05	1160	66.7	12.3	2.7	0.22	0.029
0.12	1320	160.0	20.7	3.9	0.19	0.049
0.18	1420	240.0	27.7	4.6	0.17	0.067
0.24	1470	320.0	31.8	5.3	0.17	0.077
0.30	1470	400.0	31.8	5.8	0.18	0.076
0.35	1470	466.6	31.8	6.3	0.20	0.075
0.40	1470	533.3	31.8	6.6	0.21	0.075
0.45	1470	600.0	31.8	7.0	0.22	0.074
0.50	1200	666.7	14.1	7.4	0.52	0.026

The result for the lower critical value of the superficial velocity, $V_{sup,crit}$ is strongly dependent on T_f; small changes in T_f can lead to quenching since at these temperatures (close to 950 K or so), gas phase reaction rates are very weak. Somewhat similar feature is also obtained at the highest flow rates. Between the two limits the predictions are indeed very reasonable. The fraction of convective flux in relation to radiant flux is about 20% in the vigorous burning regime and increases to near 100% on either side towards extinction. The results are sensitive to the bed temperature. This is the limitation of simple one-dimensional approach. Allowance for slight non-one-dimensionality will help lateral transfer of heat and stabilize the flame structure and the solutions will possibly be not as sensitive to the choice of the bed temperature as this model is.

6.9 Biomass feed size and tar

The recommendation in SERI (1979) and Kaupp and Goss (1981) is to use a mix of sizes, small gasifiers with a maximum size of 50 mm and larger ones accepting even as large as 100 mm. The avoidance of a uniform size is partly to help better packing, but more importantly to help better performance. Sizing the logs of wood is a more expensive proposition than chipping and producing flakes. Commercial demands for the supply of chips for paper industry is for flakes 1 - 3 mm thick, 10 to 50 mm sides. While control of the chipping process can produce 3 to 5 mm thick and 30 to 50 mm sized pieces, this option must be specially exercised. Either of these alternatives is perhaps imposed on the designer who may want blocks with all the dimensions of similar magnitude, say 10 × 20 × 30 mm, or 30 × 40 × 50 mm or 50 × 60 × 70 mm or some combination. In the southern part of India, coconut plantations are very large (1.8 million hectares, see Table 2.6) and there is a huge industry around coconut oil production. Coconut shell is then an industrial waste that is traded heavily. A large part of the coconut shell goes into char production which is further used in activated carbon industry. There is also a demand for it in gasification based power projects. The price of coconut shell when procured in large amounts is lower than for wood blocks in some areas and some seasons. This then becomes a motivation to use coconut shell in the same gasification system meant for wood.

Coconut shell has a shell thickness of 5 to 7 mm and the lateral size can be 50 to 100 mm depending on how the shell is broken to pieces. It has been the experience in closed top systems that the tar production with the use of coconut shells is very significant. In the open top design, there has been no tar related issue in the operation of the system on coconut shells.

However, if the lowest thickness based wood flakes (1 – 3 mm thick) are used the tar generation is significant (0.8 – 4 g/kg). It is therefore useful to rationalize the observed behavior of the gasification systems. Take two cases one with large size wood and another wood flakes. At a fixed throughput, the mass generation rate of the biomass is the same in both the systems. In the first case, one obtains a hot tar of 0.1 g/kg and in the other, 0.8 g/MJ. This implies that the tar cracking due to char is inadequate in the second case. To understand this behavior, we make a simple estimate of the heating rates of biomass. We recognize that the raw biomass one/two layers above the burning zone will receive the heat principally by radiation. The heat balance for a biomass particle of size d_0 is the same as eqn. 6.5. The key parameter that distinguishes the geometric feature of biomass is $m/\rho_p A_s$. For rectangular pieces of dimensions, l, b and h, this parameter is given by $lbh/2(lb + bh + lh)$. For $l = b = h$, this becomes $b/6$. For a thin flake of thickness $h = t_h$ and $l = b$, we get this parameter as $t_h/2$ for $t_h/b << 1$. The heating rate is given by

$$G\rho_p c_p \frac{dT_p}{dt} = f_{view}\epsilon\sigma(T_f^4 - T_0^4) - h_c(T_p - T_0) \tag{6.12}$$

The geometric feature G is $d_p/6$ for a sphere, $b/6$ for a cube and $t_h/2$ for a flake. Measured heating rates of 10 mm particles is about 480 K/min for pellets of density of 1200 kg/m^3 corresponding to net heat flux of about 20 kW/m^2. When scaled to 50 mm size particle this translates to 96 K/min. For 3 mm thick wood flakes with density of 600 kg/m^3, the heating rates will be about 1000 K/min. For wood cubical pieces of 50 mm size, the heating rates will be about 200 K/min. Thus a flake of 3 mm size experiences about five times the heating rate compared larger size wood piece. If we factor in the feature that heating rates of 1000 K/s imply liquid fractions of 60% of the weight of the biomass (with fine particulate matter). it appears that biomass with small thickness will generate more volatile matter. If larger size pieces are subject to high heating rates, it will be responded to by the outer layers and subsequently, the char will act as an insulator for the penetration of heat into the solid mass. The rest of the biomass will experience much less heating rate. However, with small size pieces, the heating rate will be responded to by the entire mass since what matters for heat penetration is the thickness. The combined effects will enhance the difference between the flakes and the larger pieces in terms of volatile generation rates and the flakes contribute to the generation of a larger fraction of weakly converted primary compounds of pyrolysis.

It is also useful to note that the change in the actual amounts of “tarry” fraction to cause observable changes would be from 0.2 – 0.3 g/kg in wood/coconut shell to 0.8 g/kg with flakes of 1 - 3 mm size which on the mass basis of biomass is not significant. However, if this material is allowed to accumulate in locations in the reactor or engine on a continuous basis, system may need to be shut down after a few to tens of hours of operation.

While it is clear from the above discussion that more of complex volatiles get generated, it is not clear that it should appear at the reactor exit, for there is a hot bed of char and air from side air nozzles to aid the break-up of these volatiles. To understand this aspect, we need to examine the behavior of the char. When one starts with larger pieces of biomass, invariably, the heating of the biomass leads to cracking and break-up into smaller pieces by the time all the volatiles get out of the biomass. Under other conversion processes with a mix of H_2O and CO_2 (with some oxygen of air as well from the side air nozzles), there will be size and density reduction. The latter occurs because the reaction with CO_2 and H_2O will be kinetic controlled and hence these reactions occur throughout the volume. These reactions are endothermic. Hence the bed temperature will drop downstream. This combination of lower temperatures and sizes causes a cessation of char reaction; the char may get further broken into finer pieces due to movement under pressure and mechanical abrasion. Thus, there is a minimum size of the char that will remain unreacted. Typically, this is about 2 mm. If we size the biomass itself to this magnitude, the volatiles generated will not get sufficiently cracked.

Thus the non-dimensional parameter characterizing the char conversion behavior is the ratio of average size of the biomass, d_b [equivalent of "Sauter Mean Diameter" in droplets – the diameter for which the volume to surface area is equivalent to the distribution of sizes = 6 (total volume)/(total area)] to d_{char}, the char size that enables conversion. This char size can be chosen as the lowest below which reaction will not occur. Thus we can invoke a non-dimensional quantity,

$$M_c = \frac{d_b}{d_c} \tag{6.13}$$

to describe the tar conversion process. If M_c is large, the tar conversion will be good. if it is very small - say close to 1, then the tar conversion will be poor. Even so, the reactor can tolerate a fairly small size to produce good quality gas. However, below a level comparable to the minimum size, the problem of tar becomes enhanced significantly. This size, it is speculated that the minimum size is close to 2 mm because the char activity below this size will be insignificant.

A point that remains to be clarified yet is: why is it that a closed-top reactor based on coconut shell produces copious tar where as the open top re-burn system does not? The answer relates to two aspects (i) the reduction zone of a closed-top system that follows the Imbert guidelines is much smaller than in an open top re-burn system. The residence time in closed top system is about 1 - 2 ms and in the open top system it is 4 - 5 ms. (ii) the zone above the air nozzles in more fuel rich in the close top system compared to the open top. Hence, closed top systems generate more tar even at nominal operating conditions with the use of fuels of small size whereas open top re-burn systems have a greater degree of robustness to convert the tars.

The combined effects make a close-top system less flexible than the open top re-burn system when it comes to sizes of biomass.

6.10 Cooling and cleaning strategies

Gas cooling and cleaning are required when the gas is to be transported over larger distances for thermal use or used immediately in electricity generation systems. In the present context of small power (less than about 2 MWe), reciprocating engines are the principal prime movers. These engines are able to accept fuel gas at ambient conditions whereas gas turbine engines need to have compressed fuel delivery.

An interesting approach that is valid only at large throughputs that use high pressure gasification is that the gases are cleaned of particulate matter by passing them through high temperature candle filters with pressure drop across the filter of about 1 atm (they also have the facility for back-flushing with nitrogen or the pressurised clean gas itself). This cleaned gas can be directly fed into the combustion chamber of a gas turbine engine without any cooling. If one uses an atmospheric pressure gasification system, it is necessary that the gas be cooled to ambient temperature and be cleaned of particulates and condensible gaseous components (tars). The extent to which one can tolerate tar or particulate matter depends on the engine and the cycle that is set for maintenance of the engine. Typically, the duration for major maintenance is once in 8000 hours of operation. Surely, one does not need to let the gasification system operate non-stop for this duration. One can expect short duration maintenance on the gasification system every 250 or 500 hours with longer shut-down maintenance every thousand hours. The reason for the choice of 250 hours is that even the reciprocating engines need lubrication and other check-up with this periodicity. If the gasification system can meet such a demand, it would be considered adequate. These requirements are considered appropriate for large power systems operating on a 24 × 7 basis. If smaller systems are required to operate up to 20 hours a day or less the solution is simpler. In such situations, it would also be necessary to use simpler cleaning systems not to make the system expensive. While it is also recognized that gasifier based power generation systems are to be operated in base load mode for better return-on-investment, some locations where there is no availability of power at all, the systems may be run for 8 to 16 hours a day and it is for such applications that alternate cleaning systems may be desirable.

The gas that comes out of the reactor will be at temperatures of 450 - 600°C and carries with it about 1 g/nm^3 dust and up to 0.2 g/nm^3 of condensible tar. The particulate matter is composed of a variety of sizes up to 200 μm. The gas is taken through a cyclone that can be designed for efficiencies of 80 to 90 %. Achieving higher efficiencies implies larger pressure drop. If the cyclone is made of a metal perhaps with forced air cooling on the outside as is usually the case, the gas temperature also drops by 250 to 300 K. This brings the gas temperature to about 250 to 300°C, the particulate content to 0.2 - 0.3 g/nm^3. The gas is passed through a direct water spray cooling system. Sometimes, it is thought that direct free convective cooling can be used to bring down the temperature to near-ambient conditions since the introduction of water for cooling produces an effluent that needs treatment. In all but very small power levels, this approach is unsuitable. The passage of dirty gas with fine particulate matter and some condensibles leads to deposits on the inner surface reducing the heat transfer capacity over a time. There will be no escape from periodic washing of the inside surfaces to maintain heat transfer capacity. Even without tar in the gas, the moisture in the gas (that will be present up to 10 %) will condense leading to the same issues of reduced heat transfer. Most usually, the combination of tars and moisture will lead to deposits of increasing thickness and need to be attended to.

We note the fact that the passage of the gas through the cooling and cleaning elements leads to pressure drop and we will need to draw the gas through these elements and deliver it at pressures much higher than the ambient depending on the engine demands. In such a case, we benefit in part, by raising the pressure of the cooling water. The essential idea is that pressurising water to get the same benefit is less energy intensive than increasing the gas pressure caused by the drop through flow in the ducting. The cooling water is delivered in the form of jets - impinging, generally so that atomisation of the spray can occur - and the jets are oriented in a way that entrainment of the gas can occur. This process of entrainment causes suction of the gas. In a normal gasification system, the pressure induced is so significant ($\sim$ 1.5 kPa) that the gasification system can be started on it without having to run the suction blower.

In some system designs there is one-stage cooling-cleaning and in others it goes up to three stages. The atomisation of the spray at high jet speeds (15 to 30 m/s) causes mixing with the gas and brings down the gas temperature. Some particulate matter and some chemicals like phenols will dissolve in water. Two stage cooling-cleaning can be understood to imply staged cleaning as well; some fine particulate matter escaping the first stage will get trapped in the second stage. In the IISc design, there is a third stage cleaning in which water at a temperature lower than the ambient by 10 to 15°C (typically 6 to 8°C) is sprayed. This cold water spray reduces the fine particulate matter as well as some tar to an extent that the gas "cleanliness" improves substantially. The basic mechanism by which this works is that fine particulate matter condenses on the fine drops and the drops are large enough to return to the sump and so the fine dust is removed. The gas path then encounters mist removing system - a complicated pathway that enables mist drops to interact with each other coalesce and drop

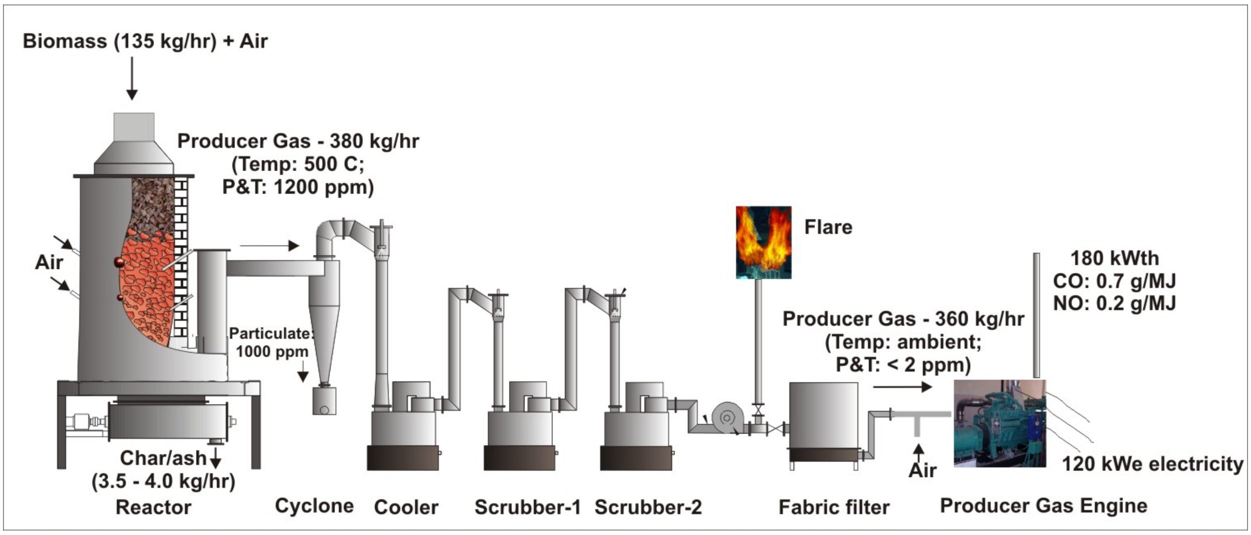

Figure 6.19: The overall gasification system - ceramic reactor, cyclone, cooler, normal water scrubber, chilled water scrubber, blower, with connections to the flare and through a security fabric filter to the engine

down. At this stage, the gas has very little tar, but fine particulate matter (1 - 10 μm) of 5 to 25 mg/nm^3 depending on the quality of the fuel itself. The gas which will be now at around 10 to 12°C passes through a blower for the pressure head to be built up. This process aids in heating up the gas to near ambient conditions, cleans up the gas to further extent and makes the gas very dry. Allowing the engine to ingest dry gas has great value in preventing local condensation due to moisture. Figure 6.19 shows the elements of the total gasification system. After the blower, the gas can be taken to a flare or to a fabric filter before being delivered into the engine inlet. At a nominal throughput, the pressure drops across various elements *in kPa* will be $-$ 2 (reactor), $-$ 0.3 (cooler), $-$ 0.3 (scrubber-1), $-$ 0.3 (scrubber-2) and $-$ 0.1 (fabric filter), totalling to $-$ 3 kPa, the negative sign indicating that the pressure is below the ambient pressure. If the delivery of the gas to the engine has to be at $+$ 1 to $+$ 2 kPa, then the blower has to be designed for a pressure head of 5 kPa. There are several other cleaning techniques that are in vogue and have been tested for a number of applications at IISc. These are reported in earlier publications (Mukunda et al, 1993); sand bed filters are commonly adopted for low power systems. The sand is sieved and fine sized particles are used to ensure removal of fine dust and tar. When diesel engine is to be connected, diesel spray for removing fine tars has been tested. In some technologies, sawdust bed has ben used as a filtering medium. M/s Biomass engineering Company, UK has a distinctive approach to gasification, particularly, the cooling and cleaning strategy. The reactor itself is the classical closed top design with modification that all the internals have ceramic lining both to preserve the heat and for material protection. One particular design practiced in a sister company in Germany seems to appear as open-top re-burn idea (Biomass engineering Co, 2010). The hot gas goes through a hot gas filter immediately after the reactor to remove most particulates. A backwash with nitrogen or producer gas is done periodically to keep the filter active. The clean gas is cooled in a heat exchanger. This also condenses the moisture in the gas (of the order of 10%). Along with it will condense tar components as well. in the Dortmund system, it appears a diesel scrubber is used. Then the gas passes through a demister to remove residual moisture in the gas before passing through a final “police” filter to the engine. The process is very elegant in its plan. The hot gas filter has a number of ceramic candles inside a larger container each of which is operated in an on-off mode sequentially. Each 250 kWe system is reported to have more than

100 candles which need to be operated periodically automatically. The question is one of long term reliability of the operations. Also, the heat exchanger will get clogged with deposits of tars over a while and need periodic cleaning or washing of the insides. These issues are being specifically pointed out because efforts in design to introduce more elements or slightly more complex ideas have difficulty in surviving over a period of time with fuel feed quality variability. This is particularly so because biomass is still thought of more we ll understood than it actually is.

6.11 Particulates, Tars and Gasification efficiency

Though much is known about the tar generation processes, there is much myth associated with tar in so far as applications are concerned. And though particulates are not considered in the same category, they can be indistinguishable from wet gas with fine particulates. In fact, the well documented work of Milne et al (1998) presents the results of a large number of gasification systems and the variation in the data set out appears bewildering. When it comes to applications as to what is an "acceptable" level of tar and/or particulate matter, there is much divergence in the values stated (FAO, 1986). Values of 25 - 50 ppm of tar, 25 - 50 ppm of particulates are some times quoted; the size of the particulate matter is rarely addressed. Size is important because particulate matter less than 5 μm will simply flow with the gas and it does not matter if even 100 ppm of this particulate matter is flowing with the gas. Further, if the application is concerned with naturally aspirated engine, it will not matter if particulate content is 50 ppm and the sizes of particulates extend to 25 μm, but if the application is concerned with a turbo-supercharged engine with a turbo-supercharger compression ratio exceeding 2. the particulate matter with size exceeding 5 μm would become unacceptable.

In so far as tar is concerned, there is wide range of definitions of what constitutes tar. Any set of materials deposited in the passages of an engine - say turbosupercharger, heat exchangers, engine valve seatings that are soluble in standard solvents like alcohols or acetone would qualify for tar. If the material passes through the system, it will not affect the operation and hence need not be feared as "tar". Hence, it is important to examine these aspects in some detail; what is more important is what causes problem to the engine and not the intrinsic composition by itself, though it may be of interest to know this composition. Therefore. it is usually thought appropriate that the "tars" be measured at the end of the gasifier to determine the quality of the gas. It is not as much appreciated that hot tar or tar in the raw gas from the reactor *be also measured* so that an assessment of the magnitude and nature of the cooling and cleaning equipment demanded to deliver a certain quality of the gas to the end application. Such tests have been conducted rarely.

One of the issues in designing the system for particulate and tar (P & T) collection is the choice of the solvent that will be used to dissolve all the tar components. When the magnitude of the tar is not small ($>>$ 100 mg/nm^3), the choice of the solvent is wider because the duration over which the sample is to be collected is small - typically fifteen minutes. If the tar magnitude is about 100 mg/nm^3, then one has to collect the sample for a much longer time to enable the chemical analysis to lead to more accurate results. This will be typically of the order of 6 to 10 hours. Over this duration the solvent must not evaporate. This will restrict the choice of the solvent to high boiling point liquids. When the tar fractions are to be extracted one needs to use vacuum distillation to remove the fragments of the solvent to preserve as many tar components as possible. Traditional solvents like alcohols and acetone are eliminated due to these considerations. Amongst the choices methyoxybenzene was adopted for tests at IISc on

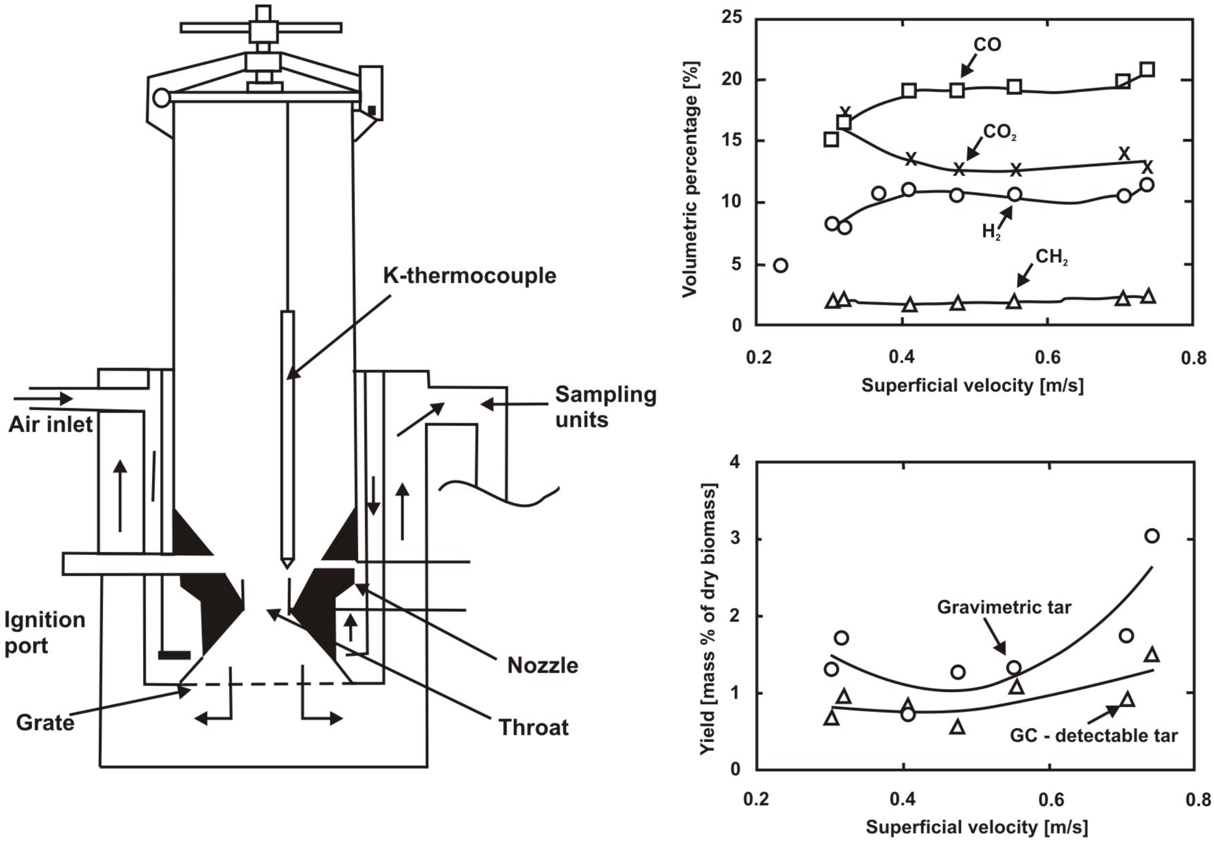

Figure 6.20: The reactor used by Yamazaki (2005) and the results of gas composition and tar production with superficial velocity

the recommendation of European partners in a test program. It is traditionally well known that one has to extract the gas sample in an iso-kinetic probe because this ensures integrity of the particulate matter. This is done by maintaining the stream speed through the sampling probe same as the mean stream speed in the duct that carries the gas to be sampled. This ensures that the particulate fraction in the sampling probe is about the same as that in the main duct. The principal reason is that particulate matter has difficulty in following the gas path if the flow is deflected due to curvature in the flow unless their size is less than about 5 μm. Since the particle sizes vary over a whole range including about a 100 μm, it is important to ensure they are either not deflected away or more than the mean amount drawn in. If the stream speed inside the sampling probe is larger than the mean speed in the duct, the particulate measured will be lower than the mean and vice versa (see Fig. 7.10 of Reed and Das, 1988). The procedures for sampling are described by EU-group (2005). Rigorous measurements have been performed on both closed top as well as open-top re-burn gasifiers. These will be described in the following sections.

6.11.1 Performance of closed-top imbert reactor

A rigorous set of measurements on a closed top system are reported by Yamazaki et al (2005) in an experimental reactor. The reactor on which measurements were made is shown in Fig. 6.20. The experiments have been conducted with sun-dry fir wood chips (5mm thick, 10 - 20 mm wide and 20 - 50 mm long on the average) with a bulk density of 110 to 120 kg/m^3.

Table 6.2: The tar composition as a function of superficial velocity; T_{bed} = Bed temperature accurate to about ± 80 K; V_{sup} = Superficial velocity

Item $V_{sup}, m/s \Rightarrow$	0.3	0.32	0.41	0.48	0.55	0.71	0.74
T_{bed}, K	944	945	1065	1211	-	1268	1243
air flow rate, m^3/h	3.0	3.3	3.6	4.3	4.7	6.0	6.7
Gas flow rate. nm^3/h	4.2	4.4	5.7	6.6	7.7	9.8	10.2
τ_{res}, s	1.66	1.55	1.29	1.1	0.96	0.75	0.70
Composition in g/kg-biomass, divide by 2.5 to get g/m^3							
Benzene	3.21	3.65	5.80	3.35	6.07	5.35	7.18
Toulene	1.17	1.41	1.84	0.98	1.84	1.63	2.24
Phenol	1.13	2.11	1.14	0.88	1.72	1.58	2.87
m- or p-Cresol	0.84	1.38	0.70	0.67	1.25	1.13	1.77
Naphthalene	0.77	1.02	1.27	0.85	1.60	1.16	1.74
Styrene	0.50	0.56	0.74	0.39	0.74	0.69	1.01
o-Cresol	0.37	0.57	0.27	0.28	0.46	0.39	0.65
Indene	0.40	0.34	0.60	0.36	0.64	0.49	0.89
Ethyl-benzene	0.21	0.21	0.15	0.10	0.20	0.16	0.29
1-methyl-naphthalene	0.20	0.27	0,21	0.14	0.28	0.20	0.34
2-methyl-naphthalene	0.13	0.10	0.13	0.08	0.17	0.12	0.21
acennaphthylene	0.16	0.27	0.24	0.18	0.36	0.39	0.48

The superficial velocity (V_{sup}) is defined as the gas flow rate through the empty throat of 70 mm dia. The bed temperature increases with the superficial velocity as expected. CO and H_2 have shown similar trends with increase in superficial velocity. The fraction of hydrogen is distinctly lower than what may be expected (is around 10% here compared to 18% typically expected). The fraction of CH_4 is about 2 %, somewhat higher than what can be expected with a good design (0.7 – 1.5%). One can estimate the gas residence time in the reactor as τ_{res} = Volume of the reaction zone/average flow rate. The volume of the reaction zone is estimated between the air entry area and a corresponding zone downstream of the throat. This volume was estimated as about 12 liters in this case. The volumetric flow rate is taken as the average between the inlet and outlet zones (average of air and gas flow rates). Then the high temperature and the porosity need to be accounted for. The average density is taken to have dropped by a factor of 3.5 and the porosity is taken uniformly as 0.5. The experimental procedure detects “hot tar”. The tar generated is classified into gravimetric tar and GC detectable tar. The gravimetric tar contains some complex tertiary compounds. While benzene and toulene can be excluded from tar, phenols, cresols and naphthalenes are a part of tar. The magnitude of tar seems large and increases with V_{sup}. The argument made for this behavior is that even though bed temperature increases, the residence time reduces and the combined effect favors greater generation of tar with superficial velocity. While the authors (Yamazaki, 2005) conclude that they have an optimum at V_{sup} of 0.44 m/s a conclusion stated to be in accordance with the work of Reed and colleagues, Other data presented here show that at these values of V_{sup}, the particulate content could be large and it would be desirable to design systems with lower values of V_{sup}.

IMBERT-Energietechnik GmbH & Co KG, 5354 Weilerswist, Federal Republic of Germany had done some interesting development work in the period 1978 - 1985 (FAO, 1986; Zerbin, 1983). The document on some test results on Imbert system of large capacity (in Zerbin, 1983) is not accessible in public domain; some important aspects presented in this report are brought out here. As early as in 1980, two plants of 50 kWe were delivered to Africa; two power plants of 60 and 125 kWe were supplied to Guyana and operated for about 12000 hours in the “most difficult” conditions with the 125 kWe system operating at a saw=mill continuously for 18 hours a

Table 6.3: Results of tests on an Imbert gasification system for electrical applications

Parameter	Low	Medium	High
Wood consumption, kg/h	180	250	290
Air intake, nm^3/h	300	400	450
Gas output, nm^3/h	450	625	720
Gas composition, volume %			
CO	28.9	20.5	18.7
H_2	11.9	16.5	18.5
CH_4	1.8	1.5	1.5
CO_2	4.5	10.0	12.8
O_2	0.4	1.0	<0.1
N_2	52.5	50.5	49.3
The following are in ppm			
C_2H_6	155	135	203
C_2H_4	324	588	976
C_2H_2 + C_3H_8	10	4	9
C_3H_6	40	33	57
Benzene	118	119	158
Toulene	9	6	21
Total minor compounds, %	0,7	0.9	1.4

day; in September 1982, 3 × 485 kWe systems were supplied to Loma Plata/Chacco in Paraguay and started operations in Jan 1983. The results of test on the plant conducted in Germany are revealing and are presented in Table 6.3. The measurements appear to have been made after an electrostatic precipitator (ESP) that has been a part of the gasification cleaning equipment. It is clear from this that the degree of clean up normally thought of as adequate with sand bed or sawdust based filters will be inadequate to assure uninterrupted long duration runs on turbo-supercharged engines. It may be noted that they have needed ESP despite the lower rpm (1000 rpm) engine (with larger valve openings and passages) deployed in Paraguay.

While the results are broadly acceptable, the behavior is indeed not easy to explain. The composition seems better at lower throughputs and the tar fractions as indicated by the minor compounds seem smaller. In fact, benzene is lower at lower throughputs. Stahl et al (2004) has made clear and perceptive observations that benzene and methane fractions are indicators of the magnitude of tar, a feature that was consistently observed in most of the tests conducted at the laboratory, IISc. This is also borne out by the work of Yamazaki (2005).

There is an interesting description of value in the FAO report on the operational experience in Paraguay (perhaps subsequent to the report of Zerbin, 1983). The experiments conducted on the gasifier in Germany before the plant was despatched were made with Pine. The fuel available in Paraguay was “Quebracho blanc” variety. This is a hardwood that might even have some oil as it is considered very valuable for furniture (as an aside, the economy of Argentine is contributed to by forests containing these trees). When this was tried, apparently, the tar fraction was more significant. The team then introduced a separate air nozzle drawing air through a duct that is introduced into the central zone. While the precise reasons for the introduction of the air nozzles are not clear, it is interesting to note that changes were to be introduced at site because of field related issues generally intended to be avoided; handling surprises in the presence of a client can be embarrassing and expensive.

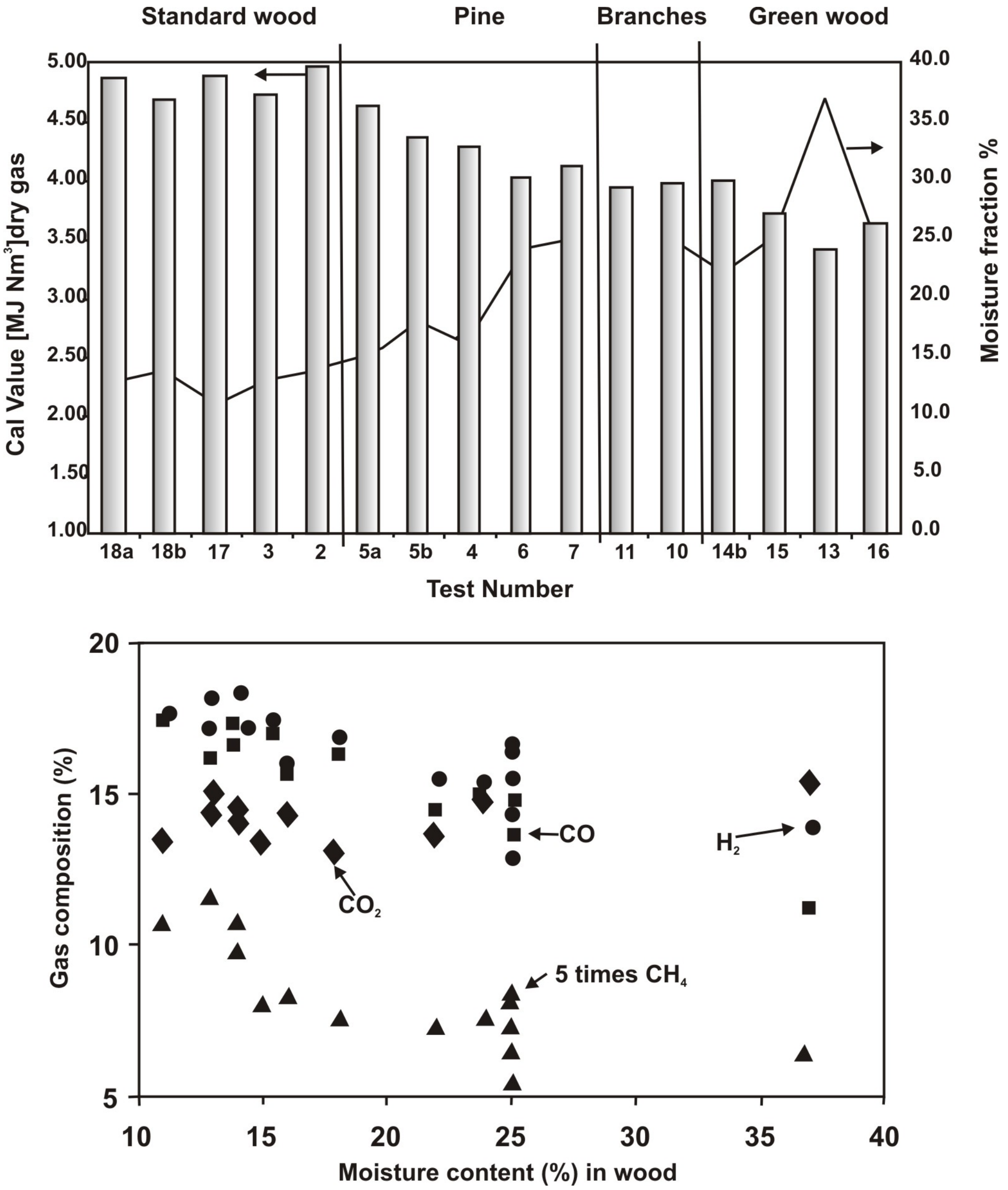

Figure 6.21: Top: Gas calorific value for several tests of biomass with various moisture fraction, the numbers 18a, etc refer to the various tests conducted; Bottom: Gas composition with moisture content of biomass

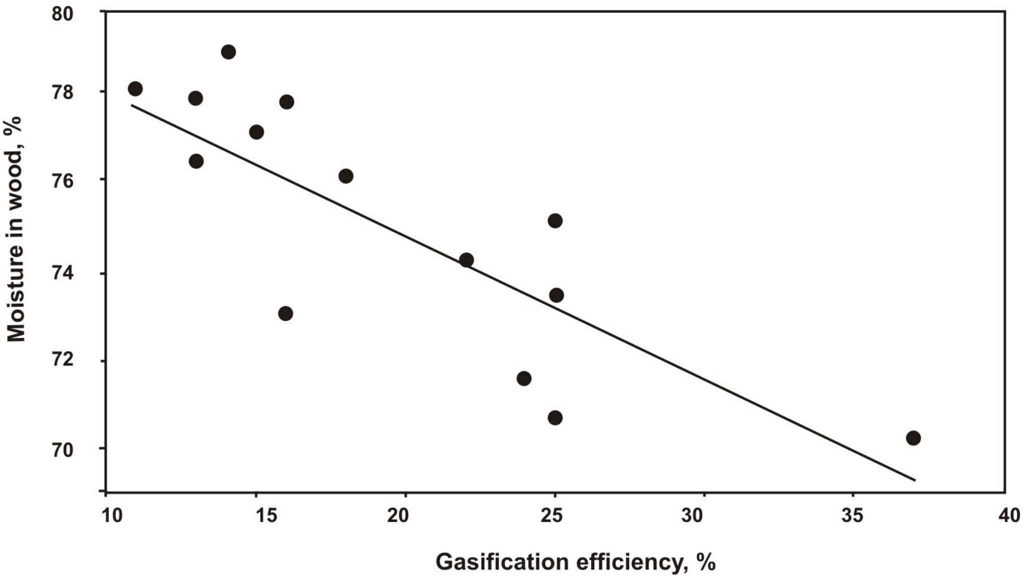

Figure 6.22: Gasification efficiency vs. Moisture in the biomass

6.11.2 Performance of open top re-burn gasification systems

The gasification system underwent five tests at the laboratory (IISc) on a 75 kg/h gasification system at three throughputs (24, 40 and 72 kg/h throughput of biomass) and two different classes of biomass (wood and cut branches of biomass with bark left as it were) with measurements of flow rates, selected temperatures, hot and cold particulates and tar (P & T). Subsequently, a similar gasification system was set up at a site in Switzerland and measurements made with more number of tests. The results of P and T, and effluent analysis were made in several laboratories in India and Switzerland. These were then synthesized after suitable review.

Figure 6.21 shows the lower calorific value of the gas for a number of biomass with different moisture fraction. The calorific value comes down with moisture fraction. As can be seen, some test results correspond to 37% moisture content. The composition for these tests are presented as a function of moisture content. It is clear that the composition becomes weak with increase in moisture fraction. One can compute the gasification efficiency, measured as the ratio of the calorific value of the gas divided by that of the biomass - η_{gasn} = (Gas flow rate/kg biomass) × gas calorific value/ calorific value of biomass. This is plotted against the moisture fraction in Fig. 6.22. The plot has some scatter; yet it is clear that the efficiency decreases with moisture content in wood. *The implications are very significant*. It appears that there is double loss by allowing more moisture to get into the biomass. The process of gasification itself is affected by the presence of moisture, largely by the effect of reduced temperature. Consequently, the calories carried in the gas will have a lower fraction of the energy of biomass which itself will be lower because of the presence of moisture. This feature is true even when one intends designing an efficient combustion system. Firstly, additional heat is put into vaporizing the moisture and raising it to high temperature. This is one loss of energy. The lowered peak temperature implies that the heat transfer efficiency will be lower. Thus drying the biomass by using low grade heat will truly benefit the performance.

The particulate and tar (P & T) measured in several tests both of the raw gas and the cleaned gas at several throughputs are presented in Fig. 6.23. The particulate content of the raw gas goes up to 700 mg/nm^3 and the tar content up to 160 mg/nm^3. The cold particulate matter and

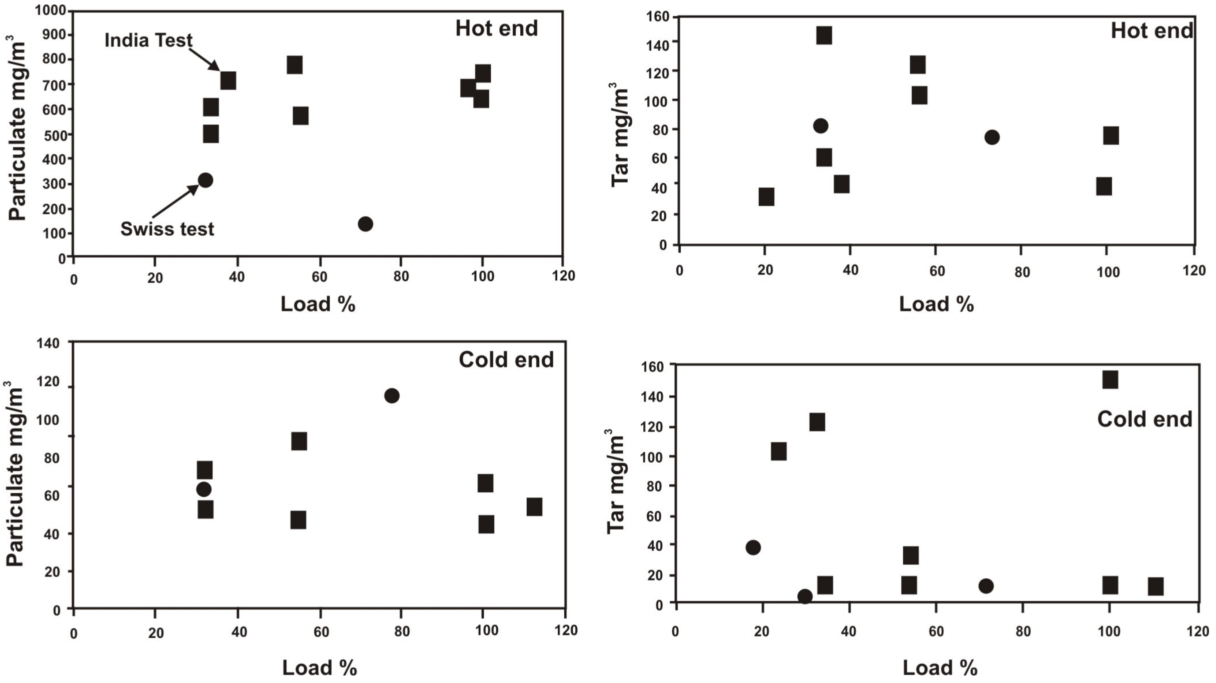

Figure 6.23: Particulate matter and tar at hot and cold ends for tests in India and Switzerland with load - 33, 55 and 100 % corresponding to 24, 40 and 72 kg/hr of biomass

tar are about one-eighth to one-tenth of those in hot condition. In a few cases, it was difficult to distinguish between tar and particulate matter. These experimental data were the basis of a gasifier that produces final particulate matter and tar of the order of 1 ppm or less. The elements that were introduced later included a high efficiency cyclone and a chilled scrubber. The P & T from the gasifier were subject to detailed analysis in a collaborative project with the Royal Institute of Technology (Sweden). These showed the tar is composed of tertiary process products (Jayamurthy, et al, 1997). The size distribution of the particulate matter of the clean gas entering the engine for the field system in Switzerland is presented in Fig. 6.24. The magnitude of the particles in the raw gas was 960 mg/nm^3, 95% is in 12 to 50 μm and the rest below 12 μm. The clean gas has 48 mg/nm^3 of particulate matter out of which 99 % is below 2 μm. This level of cleanliness of the gas ensures long term unattended performance demanded of the system. Subsequent to this, rigorous tests were conducted on a field system (see ABETS, 2010) that was designed for 500 kg/h, but was operated in the tests up to 210 kg/h with tests lasting 6 to 9 hours of P & T collection. These tests also had the participation of Swiss scientists like in the earlier ones. These tests were intended to clarify if the use of agricultural residues would alter the performance of the system. The test results are presented in Table 6.4. Two tests were performed with mulberry sticks. Mulberry is grown around this area as the leaves form the feed for silkworms. The sticks have only a domestic fuel value and is abundantly available. This was the reason for the choice of this fuel. The third test had some operational issues leading to larger generation of CH_4 and hence tar as well. In fact, there is an anomaly in the third test that shows that the cold tar is higher than the hot tar that defies explanation excepting possibly an experimental defect. The composition of the gases is nominal and reasonable.

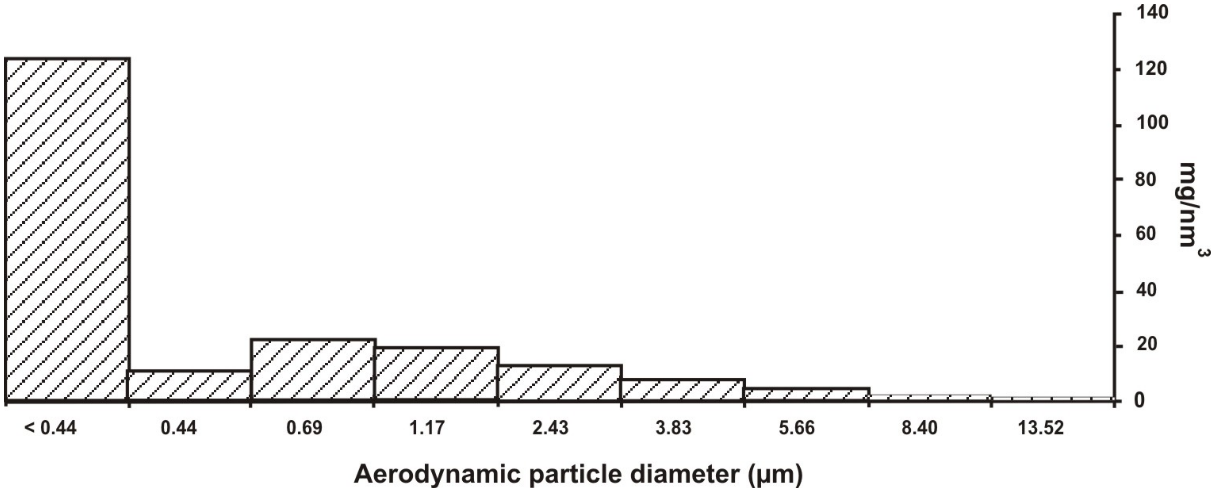

Figure 6.24: The particle size distribution of the clean gas going into the engine

Table 6.4: Results of gasifier tests in a field system (Ramanagaram); T_{ree} = Reactor exit gas temperature

Biomass	Throughput kg/h	T_{ree} °C	Composition, vol, % CO, H_2, CH_4, CO_2	P & T, hot mg/nm^3	P & T, cold mg/nm^3
Causarina	180	550	26, 11, 1.5, 7	186, 172	46, 17
rounds	210	500	16, 18, 1.8, 13	269, 116	6, 15
Mulberry	144	480	28, 14, 3.0, 12	161, 128	28, 137
Sticks	210	460	22, 15, 1.2, 12	189, 156	13, 17

6.12 Issues with agricultural residues and gasification test results

It has already been pointed out in Table 4.1 and the discussion on the table that a large number of agricultural residues have fine size and various levels of ash. One approach to use them in a thermo-chemical conversion process would be to pulverize the light residues to a relatively uniform size and use them directly. The thermochemical conversion device would be a cyclone combustor or gasifier. While cyclone combustors have been known, cyclone gasification systems are little known. A five year effort of research and development was mounted at IISc laboratory under a MNRE grant to explore this approach since what was required was drying and pulverizing before use; briquetting would be an energy guzzler, it was thought. Gasification required that both fuel and air had to be controlled independently unlike solid fuel gasifiers discussed earlier. This effort showed that gasification can be conducted well provided a good control system to manage the fuel feed corresponding to a given demand was also used. However, the gas quality, particularly, the tar content was very sensitive to the air-to-fuel ratio. One could rarely be sure of the "tar" levels. After much consideration of the examination of various aspects related to pyrolysis and other reactive processes, it was concluded that the approach to use fine biomass directly, particularly in a cyclone system even with a large residence time for the gas inside the cyclone would not assure desired low tar levels. In any case, it would be very difficult to provide an assured performance with this strategy. The reason for this behavior was understood to be due to the fact that biomass in fine form impinges on the hot wall of the cyclone and the high heating rate creates conditions close to fast pyrolysis. This leads to the generation of a gas phase composition that has a large fraction of "liquids" in vapor form. This material is processed by the hot environment with occasional contact with oxygen of the air with reasonably large residence time and tar cracking does take place. Yet the magnitude of tar is so high to start with that the gas exiting the reactor carries tar much larger than what

Table 6.5: Properties of biomass influencing ash fusion; ρ_{bulk}, ρ_{briq}, ρ_{b-briq} = Densities of the bulk material, briquettes and briquettes in bulk (when loaded in a container)

Biomass	ρ_{bulk} kg/m^3	ρ_{briq} kg/m^3	ρ_{b-briq} kg/m^3	Ash %	T$_{ashfusion}$ °C
Rice husk	100	1000	450	20	1650
Coconut coirpith	50	900	350	8	1150
Groundnut shell	120	800	300	6	1220
Pine needles	80	800	300	5	1350

Table 6.6: Critical superficial velocity, V$_{c,sup}$ for ash fusion for several biomass

Biomass briquettes	V$_{c,sup}$, m/s
Rice husk	0.21
Coconut coirpith	0.30
Groundnut shells	0.26
Coffee waste	0.17
Mustard stalk	0.14
Sawdust	> 0.5

would happen in a downdraft fixed bed system using larger size solids. It is this understanding that needed a different pathway for dealing with fine biomass. Having shown that processed wood can be used quite effectively with open-top re-burn downdraft systems, it was thought that briquetting would be the only other way of dealing with light and fine bioresidues. Such an approach would be helpful in the economic transportation of the fuel as already evident in the market.

The question then was: would the agro-residue based briquettes create any other problems in their use in the gasification system. The suspicion is that the presence of potassium in the residues may reduce the ash fusion temperature and hence it is necessary to determine this parameter. The data on some fuels is set out in Table 6.5. The data in the Table 6.5 shows that coconut coirpith has the lowest ash fusion temperature and rice husk the highest. Kaupp (1984) has brought out that the ash fusion temperature measured by standard tests can only be indicative of the behavior and when there is an air flow through a combusting packed bed of rice husk, particles attach to each other and fuse when the superficial velocity exceeds about 10 cm/s even when the average bed temperature is well below the ash fusion temperature - in this specific case, the bed temperature will be close to 1000°C. Also, attention on this subject has been focussed earlier in Tables 4.1 and 4.10 and the issues of potassium and sodium discussed in section 4.13. It is therefore important to determine what happens in a packed bed. Towards this, a simple experimental set up called reverse downdraft gasifier was put together to determine the superficial velocities beyond which ash fusion occurs. Figure 6.25 shows the elements of this apparatus. Air from a blower is passed from the bottom of a cylindrical container. The superficial velocity is obtained from the measured air flow and the internal open cross section of the container. The container is loaded with pellets or broken briquettes and lit at the top after it is sprinkled with alcohol or kerosene. The bed will establish into a gasification mode soon afterwards. The experiment is run until most of of the fuel is burnt and the system is allowed to cool down. The top region is then examined for the presence of nodules and fused ash pieces if any. The material is taken as fused when a fair amount of individual pieces cannot be easily separated. Table 6.6 presents the superficial velocities for several biomass briquettes that were tested. A surprising feature of Table 6.6 is that rice husk in the raw form will fuse beyond a V$_{sup}$ of 0.1 m/s whereas as a briquette it seems to stand up to 0.26 m/s before ash fusion begins. Sawdust used in the above experiments had ash no

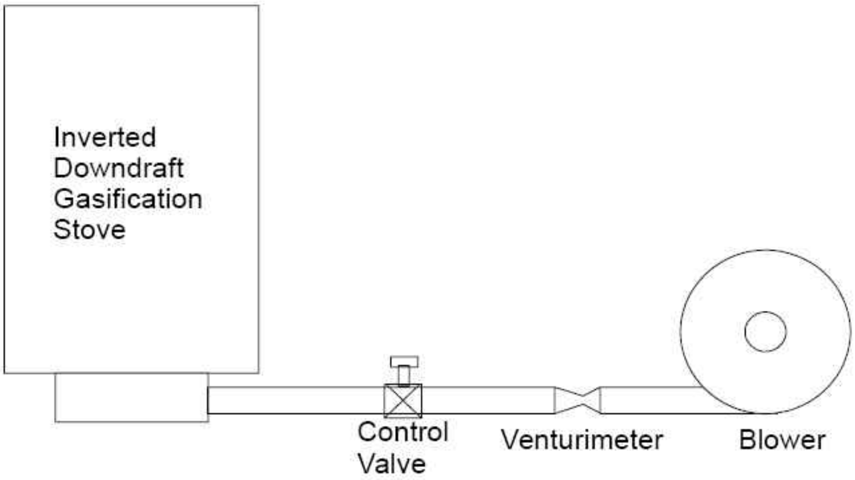

Figure 6.25: Apparatus to measure ash fusion properties with superficial velocity in a packed bed

Table 6.7: Performance of briquettes in the gasifiers: 400 mm dia reactor, 75 kg/h capacity; [a] 300 mm dia reactor, 10 kg/h capacity

Briquette	Size mm dia, mm long	Ash %	Throughput kg/hr	Composition, (v, %) CO, H_2, CH_4, CO_2	LCV MJ/nm^3
Rice husk	35, Spirals	20	30	15, 12, 1.8, 15	3.0
Sawdust	50, 35	3	54	20, 18, 2, 13	4.6
Pine needle	50, 50	2.7	8[a]	18, 12, 1, 9	3.3
Coconut coir pith	50, 40	8	44	16, 8, 1, 12	2.6
Mustard stalk	50, 50	14	35		3.5

more than 1.5 % and hence seemed to contain very little of problem creating elements. The design of the gasifiers must ensure that the V_{sup} does not exceed this value. When it refers to a gasifier, what matters is the local velocity and the allowed local velocity will be about 2 – 2.5 times higher because the bed is occupied by solid material (with a porosity of 0.4 to 0.5). Even if the design keeps to these norms, one will get some fused mass because of the non-uniform bed behavior with local velocities going beyond the condition that causes ash fusion. If this norm is seriously violated extensive fused mass will get formed preventing the operation of the gasifier in relatively short time (of hours). Urban solid waste is composed of many kinds of biomass depending on the season in addition to pick-up of sand, mud and grit that contain ash fusion aiding material. Hence, the material must of course be cleaned, a matter discussed earlier, but even so, the design must be made on a conservative basis to ensure continuous operation.

The results of the laboratory experiments to examine the behavior of the briquettes based on the above agro-residues and others (that were requested) are discussed presently. These experiments were of 2 - 3 hours after the system was stabilized on the biomass studied. Table 6.7 shows the details of the biomass, the throughput, the gas composition and the LCV of the gas. It is clear that the same system works well at 50 to 80 % of the nominal capacity whatever the briquettes are. During the operation of the system, the char is extracted at a time when loading is done at a rate dependent on the ash content of the fuel. When the systems were unloaded after each of the experiments, it was noted that there were several small nodules and some larger fused matter as well. Since the gasifier had a screw arrangement for the extraction of the ash, this did not pose an issue. What is surprising is the behavior of gasifier the with rice husk briquettes. Its operation was smooth being no different from woody biomass. Coconut coirpith considered one of the difficult fuels to deal with (because of the presence of potassium and sodium) showed that it worked well at reasonable throughputs in the reactor (44 kg/h).

A natural question to raise is whether as-received rice husk cannot be directly used in the open top system, particularly when the screw-extraction system for the char is in place; further, Can the re-burn option be exercised to improve the gas quality as in the case of solid fuel reactors discussed in section 6.7.5?. These points become important since the approach for the use of rice husk discussed here, namely briquetting is unique. This has been discussed briefly in section 6.9 but will be explained in some detail below.

Due to the low density of the as-received rice husk, the pressure drop that the bed offers is small. The bed itself is resting on a grate that is rotated to take away the char from the reactor (see Fig. 6.9). This creates a disturbance to the bed that travels upwards from the grate. These disturbances create some times local air pockets. It is clear that such a behavior exists because if one observes the open top, one can see on occasion a sinking of the bed at odd locations. Such small changes in the rice husk bed thickness (sometimes it is not small change) lead to short-circuiting of the air flow along these paths a little more than in other parts of the bed. These properties of a fixed bed of light material like rice husk are intrinsic to the nature of the fuel. These lead to random fluctuations in gas quality - both composition and tar level. One way of managing with this problem is to use an intermediate gas storage of reasonable volume to ensure that the power generation is weakly influenced. Operating without a gas storage leads to inevitable fluctuations in power if a gas engine is used. If however, the gas is used in diesel engines in a dual-fuel mode, the problem of fluctuating gas quality is handled by the diesel governor that will pump varying amounts of diesel to maintain the quality of electric supply. Most applications in India belong to this category.

The next aspect on whether exercising the re-burn option will improve the gas quality as with solid fuels needs clarification. When the reactor is operated with air-nozzles closed, the flame front will progress towards the top. This is opposed by the bed movement towards the bottom because of the char extraction at the bottom. the combined effect may imply an up or down movement of the flame front of a small magnitude. If the power demand increases suddenly, the flow rate through the reactor increases and the bed will try to move down until the thermo-chemical conversion process picks up to deliver the required combustible gas. At this stage, the flame front will stabilize at a new position or move around slightly. This flame position is a dynamic variable and may get positioned around, above or below the air nozzle. If the internal flame is located around the air nozzle, the flame is augmented. It may happen that the augmentation leads to fusion of the char. Or if the air stream speed is high, the flame may quench because the heat generation rate of the char reaction with air will not be able to maintain the high temperature. Rice husk char reacts very slowly (see the discussion in section 6.9). If the flame is in any location other than the air nozzle entry, the addition of cold air to a non-reactive char will only chill the gas stream. And any air entry from the nozzles will reduce the flow of air flow from the top region and so, the net result will only have negative influence on the conversion process. Therefore the air nozzles must remain closed for the gasification process to proceed.

To illustrate the benefits of briquetting some simple experiments were performed on the combustion of rice husk, sawdust, pulverised rice husk, sawdust with 20% silica and briquetted sawdust and rice husk spheres. Figure 6.26 shows three of the pictures of these experiments. When rice husk is burnt in a pile, the volatiles burn away, and subsequently, about half-the-char gets converted slowly. Beyond this point the heat generation rates cannot keep pace with the heat demand from the inert part (and some heat loss as well) and the reactions get quenched; the carbon at this stage is about half of the silica present. However, the carbon is located between silica molecules reducing the access of oxygen in air to the sites having carbon. The

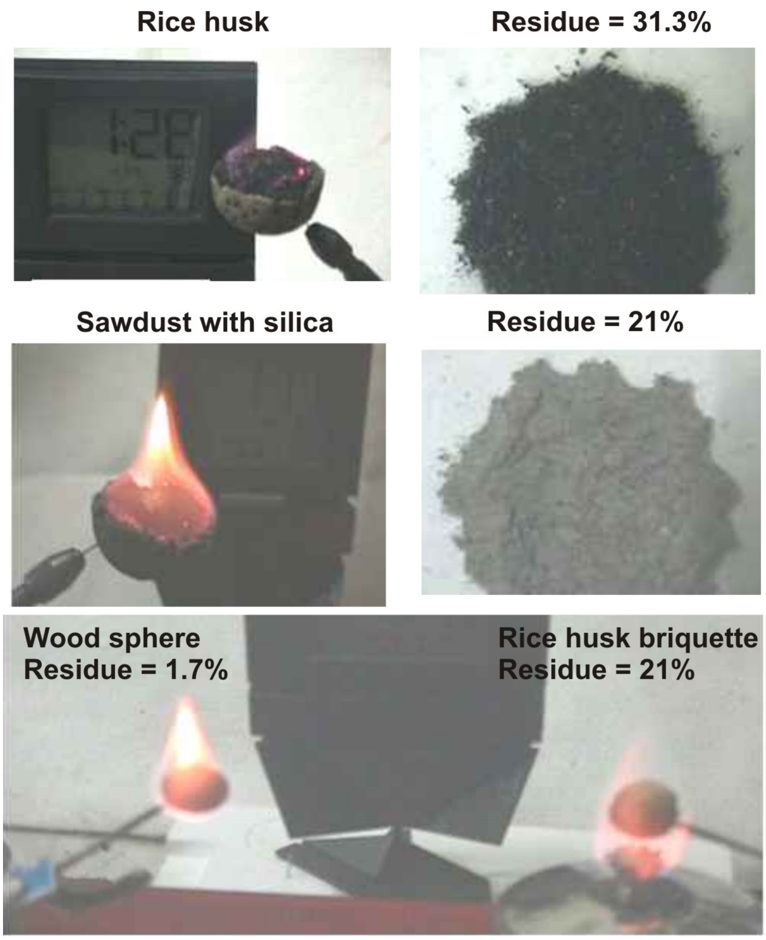

Figure 6.26: Top left: burning rice husk filled in a porous ceramic pouch; right: Residue from combustion, note that it is dark; Middle left: Burning sawdust with 20 % silica simulating the rice husk, right: Residue from combustion. note that all the sawdust is burnt away leaving behind silica and 1 % ash from sawdust. Bottom: Briquettes of sawdust and rice husk burning. Note that rice husk briquette burns away completely.

behavior of pulverised rice husk is identical to the native rice husk showing physical action at reducing the size (of course, to 0.5 to 1.5 mm) does not influence the behavior. To establish the role of structural detail of rice husk, sawdust filled with 20% silica is studied. This is the middle picture. Here, the residue is composed only of silica and ash from wood. All the fuel elements are oxidized. The carbon present was easily accessed by oxygen in air and hence combustion is completed. The bottom picture shows the combustion of spherical briquettes of sawdust and rice husk. Here the conversion is complete. The residue is ash in the case of rice husk as well. The reason for this behavior is that the adiabaticity of the rice husk briquette with small pores bringing in air by diffusion appears adequate to convert the rice husk char. *This is the fundamental basis* for converting all bioresidues that have reasonable amount of inerts into solid form - briquettes with expectations of required amount of conversion. Further, tests were conducted at Suranaree University in Thailand with a 100 kg/hr gasifier for rice husk briquette as fuel built by M/S Satake. The plant was initially coupled with a Komatsu diesel engine of 134 PS rating. The plant was operated in dual-fuel mode to essentially gain experience using wood chips and rice husk briquettes. The required briquettes were produced from a 100 kg/hr rice husk briquetting machine (Japanese make) installed within the premises. The spirals measured 40 mm (L) x 50 mm (dia). The gasifier was coupled to a Cummins gas engine G855G

Table 6.8: The mass and heat balance of the gasification – power generation system; Fuel throughput: 100 kg/h sundry wood, LCV = 15.8 MJ/kg; Power input = 440 kW; E = Extracted, I = Introduced

Item	Gas flow kg/h	Temp. °C	Power kW	P & T g/h	Comment
Reactor exit	270	500	370	270	E – 5 kg/hr, 30 kW (char/ash)
Cyclone exit	270	250	350	60	E – 0.22 kg/hr, 7 kW (carbon/ash)
Cool-clean inlet	270	250	350	60	I – 30 m^3/hr water
Cool-clean exit	240	12	332	2	E – 30.02 m^3/hr water
Filter exit	240	20	332	0.5	
Engine inlet	240	20	332	0.5	I – 330 kg/hr air
Engine exit	570	300	110		E – 140 kW cooling water
Electricity			98		Fuel – Elec. eff. = 22.3 %

of 80 kWe nominal output. Operations on the gasifier was steady with pressure drops in the nominal range with a char extraction of 25%, This extraction rate corresponds to the native ash content of 19 - 20%. Measured gas composition was 17% CO, 15% H_2, 2%CH_4, 14% CO_2 and rest nitrogen. The performance on the engine will be discussed in the next chapter (section 7.6).

6.13 Heat and mass balance of gasification systems

The heat and mass balance of the gasification - power generation system is shown in Table 6.8. The values indicated are consistent with the general description of the system performance presented earlier. An important point to note is that the hot gas has 11% moisture (10 to 12% generally). During cooling this will leave the gas stream. Thus the mass flow rate of the gas decreases. The fact that the hot gas has a higher temperature is compensated by the cooled gas having lesser inert mass. Thus the energy intensity is maintained.

6.14 Liquid effluents and water treatment in gasification systems

The gasification process brings the gases into the cooling and cleaning system with 150 - 200 mg/m^3 of particulate and tar (P & T). The cooling process brings down the temperature and hence some of the constituents that dissolve in water will get off-loaded. Large particulate matter (up to a size of 100 μm) also will come into contact with water. A significant part of the particulate matter is also washed out of the gas here. The process occurs in two stages broadly separated as cooling and cleaning; however, both sections are involved in the scrubbing action. This process brings down the particulate and tar in the gas to about 20 to 30 mg/nm^3. Beyond this stage the chilled scrubber takes away about 15 - 25 mg/nm^3. Thus we have two classes of cooling waters carrying 130 to 170 mg/nm^3 and 15 - 25 mg/nm^3 of P & T. These are to be handled separately since the first set is at ambient + 2°C and the second set at 10 to 12°. The requirement for water treatment of the cooling water arises from three considerations. (a) Beyond a certain loading the flow rates in the cooling circuits will come down because of deposits of this matter near the injector holes. (b) The chemicals dissolved in the waters are foul smelling and (3) There are pollution control board norms that prescribe the quality of waters that can be discharged from the system. One does not need any treatment if there is only one pass for water. This can happen in water pumping applications for agriculture. The water is pumped through the cooling circuit and discharged as water for agriculture. This discharge meets the requirements of pollution control board. The typical composition of the contaminants in the

Table 6.9: The typical composition of the cooling waters; mfw = moisture-free wood

Item	P & T	BOD	COD	Phenols	DOC	NH_3/NH_4
g/kg mfw	1.45	0.14	1.9	0.08	2.32	1.72

Table 6.10: Composition of the effluents - untreated, treated and the pollution norms; Ind. + India, Ch = Switzerland; U = untreated, T = treated

Item	U Ind.	T Ind.	Norm Ind.	T Ch	Norm Ch
Color	Brown	None			
Odor	slight	None			
pH	7.8	7.5	6-9	8	6-9
Conductivity, μmhos/cm	1804	1650	2250		
All the values below are in mg/liter					
Suspended solids	212	4	100		
Dissolved solids	704	1012	2100		
Hydrocarbons				6.0	20
Chlorides	185	117	1000		
COD	215	16	250		
BOD	129	1.5	30		
Kjeldal Nitrogen	223	50	100		
Ammo-cal Nitrogen	128	28	50		
Ammonia (free)	7	0.2	5		
Sulphates	52	111	1000		
Oil and greese	<1	<1	10		
Ni	<0.01	<0.01	3	0.16	2
Hg	<0.001	<0.001	0.01		
Hexavalent Cr	<0.01	<0.01	0.1		
Pb	<0.01	<0.01	0.1	0.06	0.5
Cyanide as CN	-	-	0.2	0.06	0.5
Cr	<0.01	<0.01	2	0.009	2
Zn	<0.01	0.03	5	1.84	2
Cu	<0.05	<0.05	5	0.08	1
Co				0.1	0.5
Cd				-	0.1

cooling water are presented in Table 6.9.

Understandably, it is the COD that dominates the effluent, as much as ammonia. These values will depend on the feedstock. The treatment process should remove the particulates and dissolved chemicals. Since the particulate content is small, the addition of a flocullent is needed. This will help bring the fine particulate matter together into a lump to further allow it to settle down. This material is periodically withdrawn, dried and disposed. This material constitutes 1 – 1.5% of the biomass throughput and is composed of 60 % carbon, the rest being inorganic material from the ash of the biomass and the flocullent. A detailed composition of the effluent before and after treatment is presented in Table 6.10. Shown are the results of analysis from two commercially operating system in India (1 MWe capacity) and Switzerland (55 kWe capacity). There are differences in the norms imposed on the discharge of the effluents in the two countries. The pH of the untreated effluent is close to neutrality. The magnitude of dissolved solids is more in the treated sample compared to the untreated one due to the fact that a part of the flocullent enters the liquid. Most other components are much below the norms set for discharge in both the countries including heavy metals. The magnitude of Zinc is close to the limit but within the norm in the case of Swiss system.

6.15 Summary

This chapter is concerned with discussing many aspects of gasification - principles, the results of experiments on gasifiers and the elements of technology that work, the emphasis being to connect the observations to the fundamental processes. Gasification is a process that employs slow pyrolysis that converts the solid fuel into largely a gaseous fuel. It is further processed in a reactive environment of char at as high a temperature as the aero-thermal processes permit to generate "minimized" tar filled gas to enable use in engines for electricity generation or high grade heat that can be piped.

In the study of the subject of gasification, the pathways of pyrolysis and the chemical kinetics have been examined greatly in the literature. Inferences on the importance of the kinetic steps are set out; the role of catalytic effects of some oxides native to a particular species will become important. If this were indeed to be true, the gasification process must be come sensitive to the species. That it is not so is widely appreciated because the precise biomass - pine, cidar, eucalyptus, ipomia, quadrecho blanco does not matter and even agricultural residues are intended to be used without a second thought. The only reason is that no matter what influence the catalysts have in producing widely different complex chemicals during the pyrolysis regime, the oxidative gas phase processes will degrade these into other fragments which cannot be traced back to a particular species. Thus, when the process is understood as aero-thermo-chemical in nature, the role of pyrolysis becomes subdued; it may help identify which pathways lead to what class of chemicals in tars.

Many aspects on gasification are well known – it occurs at an equivalence ratios of 0.3 – 0.4, the energy captured in gasification varies between 4.6 to 6.5 MJ/nm^3 with larger calorific values obtained with higher CH_4 content. The presence of larger fractions of CH_4 implies the presence of larger amounts of higher hydrocarbons and oxygenated compounds called tar. Processes that generate in the order of decreasing amounts of tar are updraft fixed bed, recirculating and bubbling fluid bed systems, downdraft closed top and open-top re-burn systems. The thermo-mechanics of these processes that control the tar are described in some detail. Ensuring higher temperatures and a larger char bed are very supportive of tar reduction to simpler molecules. Systems other than the open-top re-burn systems have a significant fraction of benzene, toulene and naphthalene. While the fraction of naphthalene is still small in classical closed-top systems it is a somewhat dreaded compound in other systems where the gases are not adequately processed in the reactor. Their deposition in regulators and other components along the pathway to the engine contributes to serious malfunctioning and periodic shut-down (see Fig. 7.17). All ambient pressure gasification systems must have a cleaning train and the loading on the cleaning process will be enhanced if the magnitude of hot-tar is significant as it happens in all approaches other than downdraft systems.

Moisture and the biomass have significant effects on the quality of the gas. The effect of moisture shown clearly in Fig 6.22 calls for emphasis even more than others since it remains least appreciated or practiced. Biomass being as dry as possible - with moisture content not exceeding 10% is the most desired condition. The role of size has been known qualitatively for a long time. The size of the biomass in relation to the size of the char left behind in the reactor is argued to be responsible for the extent of tar generation. This leads naturally to a non-dimensional number that is the ratio of the mean value of minimum thickness to the residual char. Arguments are made to show why the tar in a closed top system could be larger for small sized biomass that will not create any issues with open top re-burn system. These need more rigorous experimental demonstration.

In so far as the use of agro-residues in small gasification systems is concerned, it appears that the practice has been somewhat divided. The use of fine residues in as-received form has issues of greater tar generation that can be overlooked at the expense of performance in terms of power generated or diesel replaced and the environmental impact. Enhancing the unit size by briquetting will improve the performance to levels comparable to woody bio-stock with performance consistent with the native ash content. The reasons for this lie in aero-thermo-kinetics - reaction of CO_2 and H_2O with carbon under better adiabatic conditions.

The presence of ash with potassium and sodium is also serious for smooth and steady functioning of the reactor (and therefore the gasifier). Increased temperatures lead to ash fusion, the higher temperatures being related to higher velocities expressed in terms of higher superficial velocities. One needs higher values to have temperatures high enough to convert the tar fragments but not so high as to cause ash fusion. This aero-thermo-chemical challenge is best handled by staged air entry into the system. The first part of the staged air entry causes flaming pyrolysis and the second part its combustion with enhanced participation of the hot char in tar conversion.

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7 Power from producer gas

7.1 Burners for producer gas

Burning producer gas is no different than burning LPG or natural gas. Most applications demand specification of peak temperature apart from the power level; some demand a short or a long flame. The important properties of several gases with air and oxygen as the oxidant are set out in the Table 7.1. Natural gas being composed largely of methane has a lower density and hence there is a difference between the mass flow rate and volume flow rate data. While any design procedure takes care of this aspect, it is an important feature to keep in mind. Biogas is rich in combustion to the extent of CH_4 in the gas and hence combustion properties are controlled by it. Since the other component of biogas is CO_2 that has a higher density, the average density is close that of air. The mass and volumetric flow rates turn out to be only slightly different. LPG is composed largely of butane (C_4H_{10}, 80 %) and propane (C_3H_8). Its density is much higher than of air. The difference in S between mass and volume units is very significant. Producer gas differs considerably from the other gases. It is composed of CO that has oxygen in it. Hence, the value of S is very much lower. The density is close to that of air (because nearly 50 % is nitrogen). Hence the air-to-fuel ratio is the same in mass and volume units. Data on natural gas-oxygen and producer gas-oxygen are also presented in the Table 7.1. These are set out because there are often requirements of melting furnaces demanding higher temperatures. For instance, glass furnaces need nearly 2000 K to maintain the melt bath. In such situations they use either a liquid fossil fuel or natural gas depending on the availability and economics. The question would be whether it is possible to replace the fossil fuels by renewable fuel like producer gas. This choice may often be rejected because of the inability to reach such temperatures in practice. What is achieved in practice will be close to 1650 K due to heat losses and compositional changes related to the quality of fuel over a period of time and factors outlined in chapter 4, section 4.8. It is not difficult to use a part of the gas to preheat the gas to conditions that will enable achieve these temperatures (see chapter 4, section 4.9 for a discussion on this aspect). Alternately, one can use oxygen if this is available and economically feasible. The peak temperatures that can be achieved are much larger than with air and can meet most industrial requirements.

Occasionally, refitment of systems running on natural gas to operate on producer gas may be

Table 7.1: Stoichiometric air-fuel-rato (S) and Flame temperature for gases

Item	S	T_f, K
Natural gas-air	17 (mass), 10 (vol)	2300
Natural gas-oxygen	4 (mass), 2	3500
Biogas (60 % CH_4)-air	10 (mass), 8 (vol)	2100
LPG-air	15 (mass), 5 (vol)	2300
Producer gas-air	1.2 - 1.4 (mass, vol)	1900 - 2100
Producer gas-oxygen	0.3 - 0.4 (mass, vol)	2800 - 3000

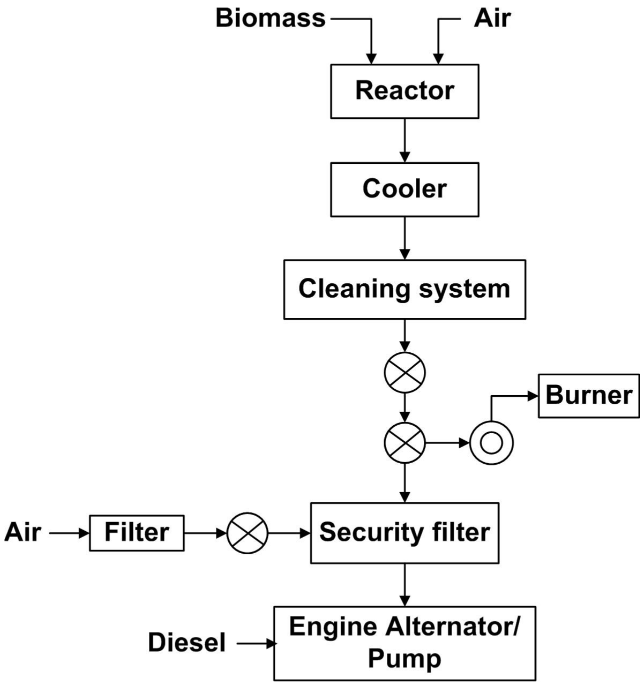

Figure 7.1: The schematics of the gasifier-engine for dual-fuel operation

demanded. In such a case, it should be noted that gas flow rates are much higher and air much lower compared to natural gas systems. Re-engineering has to be suitably dealt with. Producer gas systems have been used for melting Aluminum extensively. That they can be used in glass melting furnaces and in remelting furnaces for scrap iron through the strategies outlined above have to be realized yet.

A number of thermal applications on silk reeling ovens, cardamom drying and salt drying have been explored systematically and documented by Mande and Kishore (2007). Another application that has been brought up in various discussions is for use as piped cooking gas. The argument has been that such an arrangement was in place even in London in an earlier period and why it cannot be practiced now. At the time this was practiced in other countries, natural gas and liquified petroleum gas (LPG) were not adequately available or could be made available because of lack of infrastructure. But such is not the case at present. Both natural gas and LPG are made available in all major cities and towns. As such introduction of producer gas as a cooking fuel calls for a major re-thinking along these lines. It is to be understood that there is no technical limitation to this and in some locations in China it is practiced, but more as a demonstration. There are some villages that have biogas, improved biomass stoves and producer gas all made available for cooking in all the houses. A few of the economically better-off families have LPG as well.

The only technical issue that may be flagged with regard to the use of producer gas is safety because the gas has a significant fraction of CO. This also can be addressed through the use of CO monitors and additives to cause a smell when gas leaks as it is arranged for LPG, if it is the only obstacle.

7.2 Operation with Diesel engines

Most small power diesel engines are multi-cylinder direct injection engines with compression ratio (CR) between 15 to 21 though the most common CR is about 17. Engines of 3.7 to 60 kWe are available in naturally aspirated mode, those with power levels from 60 to 150 kWe on both naturally aspirated and turbo-supercharger mode and those beyond 150 kWe most usually in turbo-supercharger mode. Use of turbo-supercharger will increase the power output on the same basic frame. Most small engines generate electricity at 230 - 275 g/kWh at power levels $<$ 150 kWe. These correspond to diesel-to-electricity efficiencies of 30 to 35 %. Even small engines provide the efficiencies of 25%. The only issue is the cost of diesel has gone so high that the cost of electricity from diesel is 25 to 30 US cents/kWh (this must be contrasted with grid electricity at 8 to 10 US cents/kWh). Thus operating on dual fuel mode becomes an attraction if the industry/institution is being serviced by diesel electricity solely or substantially since biomass in off-city areas may be available at prices that make dual-fuel operations economically attractive (of course, not as attractive as gas-alone mode as will be seen further).

Operating a diesel engine in dual-fuel mode is relatively simple. Figure 7.1 shows the method for dual-fuel operation. The engine air inlet is connected to a piping that draws air and gas with air from air filter through a control valve and the gas from the gasifier through a control valve. To begin with, the gasifier operation is stabilized with the gas going to a flare (or a burner). When the oxygen fraction in the producer gas outlet comes down to $<$ 1 % (definitely not more than 2.5 % from the view point of safety), the gas valve to the engine is ready to be opened. The engine can be started in diesel mode during which period the control valve from the air filter is kept open. Now the flare (burner) line from the gasifier is closed and the gasifier line control valve to the engine opened. The engine will draw both air and gas depending on the relative resistances. Since the resistance from the gas line is larger (we may note that blower is not needed for dual-fueling), it will begin to draw small amount of gas. At this stage, the control valve on the air line can be turned down slowly. This will enable more gas to be drawn into the engine. It is also known that dual-fueling will make the engine run more quiet and this transition to dual-fuel mode is very distinct. The engine can then be loaded suitably. By reducing the air flowing into the engine, the proportion of power from the gas is enhanced. When the control valve on the air line is turned down to such an extent that the engine cannot take up the load, frequency will drop. This is the indication of “overloading”. At this stage, the air valve is opened a little more to a level when the engine can manage the load by maintaining the frequency. Using dry wood and proper conduct of gasifier operations, one can achieve diesel replacements of 85% at around 80% of the rated load in engines designed with sufficient excess air at nominal power. The measured oxygen fraction in the exhaust stream will be about 2 %. Beyond this point, the combustion in the engine will become fuel rich and the ability of the engine to take load comes down. Hence this limit should be observed by measuring the oxygen in the exhaust and controlling a motorized valve suitably or manually turning down the gas flow by just listening to the change in the noise of the engine.

Experimental studies have been conducted on dual fuel operation by Sridhar et al (2005) and Uma et al (2004) on small diesel engines. While the broad results by these two studies are similar, more detailed set of results available in Sridhar et al (2005) will be used to illustrate the central ideas. In this study, the authors used a ALU 680 Leyland naturally aspirated four stroke diesel engine that has a compression ratio of 17.1 with a cylinder swept volume of 10 liters and runs at 1500 rpm. It delivers an output of 75 kWe at Bangalore (1 km altitude). Figure 7.2 shows the measured exhaust oxygen fraction in diesel-alone and dual-fuel modes as a function of load. Also shown are the specific diesel consumption (kg/kWh) in both modes of

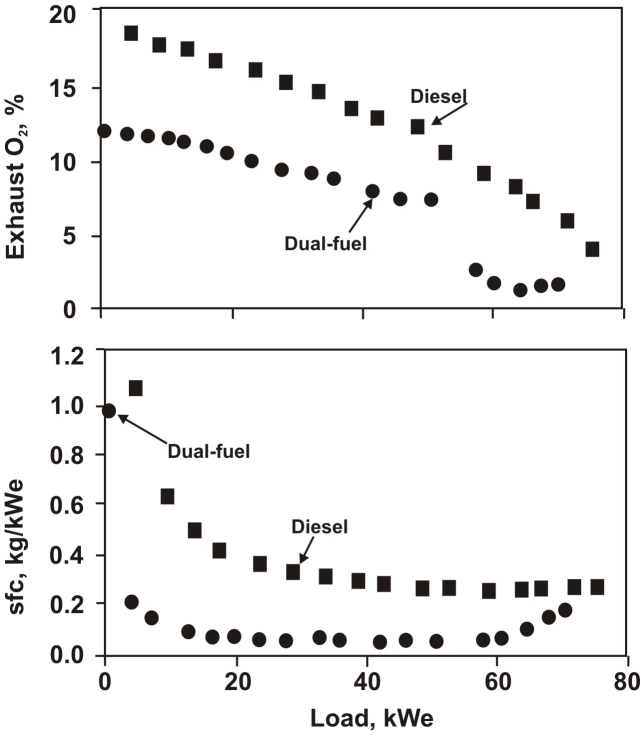

Figure 7.2: Oxygen in the exhaust stream and the specific fuel consumption with load in diesel and dual-fuel modes

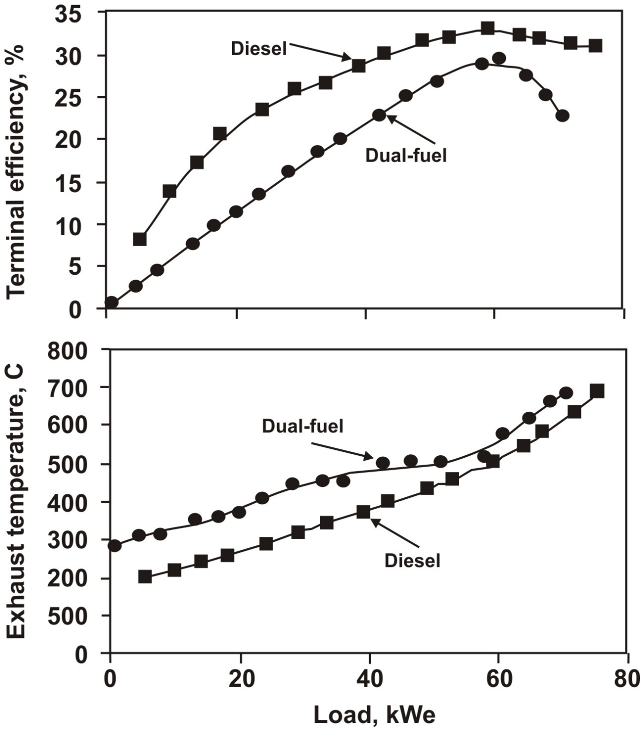

Figure 7.3: The efficiency and gas exit temperatures with load in diesel and dual-fuel modes

operation. In diesel mode, the oxygen fraction drops down smoothly till about 3.5 % at 75 kWe. Beyond this value, the engine starts smoking. It is such a condition that sets the upper limit for the power in a diesel engine. The oxygen fraction in the dual fuel mode can be brought down to levels that enable smooth operation. The oxygen levels are not small at low loads. The diesel replacement (DR) is close to 85 % in most of this regime. As the load demand moves towards the peak, reducing the oxygen down to low levels becomes important. The DR also comes down to levels of 68 % at around 65 kWe. The oxygen is first consumed by hydrogen and methane, because the fuel and air are already in a mixed state and the reaction rates are fast; diesel and CO compete for the rest for different reasons - diesel because it has to vaporise and mix and CO because its conversion is slow. It is this process that controls the power carrying capability of the engine in dual-fuel mode and also the emissions of CO. The specific fuel consumption of diesel (sfc) vs. load in Fig. 7.2 shows that sfc reaches an optimum at around 50 % load. The sfc in dual fuel is very low at most loads. The rising part of the sfc in dual-fuel mode is the segment when the diesel replacement is reducing and reaches 68 % at 65 kWe. Of course, the system can deliver 75 kWe at reduced diesel replacements ($\sim$ 40 %).

The results on efficiency and exhaust temperature are shown in Fig. 7.3. The efficiencies start off from zero at no load and reach a maximum at the nominal output, as can be expected. The diesel-alone efficiency reaches a peak of 33 % at 65 kWe and delivers the peak output of 75 kWe at an efficiency of 31 %. Dual-fuel operation reduces the efficiency at nearly all the loads with the loss in efficiency of 4 % points at 65 kWe. The accompanying exhaust temperature is always higher in dual-fuel mode than in diesel mode by about 50 - 70°C near the peak output. At full output, the exhaust becomes red hot. The exhaust temperatures of larger engines however will be around 250°C because the turbo-supercharger will absorb the energy. This process raises the diesel-to-electricity conversion efficiency substantially. The lower efficiency on dual-fuel compared to diesel-alone operation is essentially due to lower peak temperature in the cylinder compared to diesel operation leading to lower peak chamber pressures. In addition, whatever energy is present in the gaseous mixture and diesel remains not as completely used leading to higher CO and therefore, higher exhaust temperatures.

We can make a simple estimate of the total flow rate ingested by the engine as [swept volume of the cylinder × (engine rps)/2 × induction efficiency] = 10 lit × 25/2 × 0.75 = 94 lit/s = 90 g/s. The factor 2 in the above expression is due to the fact that we are considering a four-stroke engine. For the engine under consideration, the full diesel flow rate is 21.6 kg/h (6 g/s). This leads to an A/F of 15. The stoichiometric A/F for diesel is 14.3 (see chapter 4, section 4.5). Thus, this leaves little excess air at nominal operating conditions. However, in some engines the nominal condition allows for much higher A/F (typically around 20). This then becomes the point of maximum fuel consumption rate in the dual-fuel mode and maximum power. The flow rate into the combustion system *remains constant*. When diesel is injected, the combustion process leads to rise in pressure over the piston head and hence leads to work output. In the dual-fuel mode, when gas is to be supplied, it replaces a part of the air. Figure 7.4 shows the flow rates and efficiencies for diesel-alone and dual-fuel operational modes of this engine.

At an output of 75 kWe, the diesel-alone mode needs 21.6 kg/h of diesel and on dual-fuel mode it delivers an output of 65 kWe with 46 kg/h of biomass and 6.2 kg/h of diesel. This means a replacement of 68 % diesel. Its efficiency is 27.6 %. Compared to diesel-alone mode, the efficiency is lower by 1.4 % on gas-diesel mix and by 5.4 % on wood-diesel mode. The difference between gas-diesel mix and wood-diesel mix is due to gasification efficiency. The difference of 4 % points in this case (it could go up to much higher values) is due to the inefficiency in the combustion process. The combustion process in a diesel engine is the diffusive combustion of fine droplets and that in dual-fuel mode is a combined diffusive combustion as well as premixed

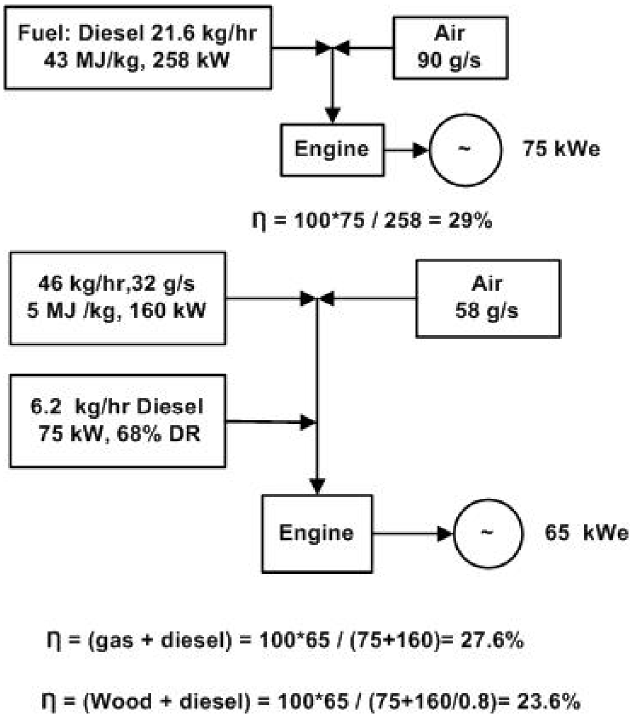

Figure 7.4: The energy flows into the engine and efficiencies in diesel-alone and dual-fuel modes of power generation

combustion of the gaseous fuel-air mixture.

This leads to a conflict - should one operate at the highest possible efficiency or maximum diesel replacement? The rising prices of diesel imply that the highest diesel replacement is most desired. On the question of maximum diesel replacement, experience reported earlier (FAO, 1986) and that at the laboratory (Mukunda et al, 1993) show that it is possible to obtain 92 % diesel replacement (only 8 % of the diesel at the corresponding load is adequate). In this condition, the diesel that is injected serves the purpose of an ignition agent, for otherwise the gaseous mixture will not ignite by itself. To maintain the replacement as high as 92 %, the gasifier operation and the load delivered have to be very steady. In practice, this is rarely the case and one can obtain diesel replacements of 85% with minor fluctuations in the load. One of the other issues is that the injector that provides excellent spray at 100% throughput has to pass 10 - 15% fuel and cause good atomization is very difficult in pressure atomizers of the kind adopted in small engines. In fact part of the limitation in achieving the full benefit of diesel replacement is because of poor atomization at reduced throughputs. If sprays are divided between smaller diameter nozzles for smaller flows and larger diameter nozzles for larger flows with suitable control to cut-off only the larger flows as needed would help better atomization and therefore ignition and hence diesel replacement. All the studies related to dual-fueling has been done without altering the fuel injection advance that is used normally in a diesel engine. This advance is 24 - 27° before TDC in most engines. Slight changes in the advance settings did not alter the performance in terms of smooth running and diesel replacements with good gas composition. Retaining the same advance for dual-fuel operation has a special advantage that when the gasifier is not functional, power can still obtained from diesel engine operation in a normal manner.

In the more recent well designed engines, the approach has been to maximise the power per unit swept volume to reduce the weight of the hardware. This approach implies that the excess air factor is very limited. In such cases, the power in dual-fuel mode may reach up to 75 % with good gas quality. Some projects in India chose highly efficient diesel engines for dual-fuel operation (in fact with rice husk gasifiers) and were able to deliver only 30 % of the diesel power. The commercial projects cleared on the basis of the power in diesel mode had to suffer losses and had to shut down.

The engines at lower power level operate at 1500 rpm. However, larger power engines, say 2 to 3 MWe operate at lower speeds, typically at 1000 rpm. Though there are engines that have been designed to operate at 375 rpm and some even at 60 rpm, these can be considered very special designs. Operation at lower rpm allows for a larger stay time than conventional systems. Typically, a 1500 rpm, 4 stroke engine has a cycle time of $2 \times 40 = 80$ milliseconds (ms) in which the combustion process from injection to completion of combustion takes about 20 to 30 crank angles amounting to 2 - 3 ms. This becomes extended to 3 to 4 ms for a 1000 rpm engine and become much larger for engines operating at even lower speeds. This helps the combustion process better; so much better that the diesel-to-electricity conversion efficiencies of 50% + have been recorded (Wikipedia, 2010). This implies a fuel consumption of 175 g/kWh. Another way of expressing this number is in terms of kWh per liter of diesel. While small engines give about 3 kWh/liter, the large engines give nearly 5.7 kWh/liter. Nowadays, somewhat routinely, 4.5 kWh/liter is promised and delivered on all large engines. One of the other advantages of the large engines is that they can burn fuels cruder than high speed diesel. Furnace oil is the one of the later crude fractions in the process of distillation of petroleum crude. It is a mix of number of higher hydrocarbons and has a very high viscosity. It has to be cleaned, heated up to 120 to 140°C before the engine can accept it. By comparison, producer gas is very clean and can be introduced into the engine in dual-fuel mode. If the gas quality is very good, one will get adequate fossil fuel replacements, but may encounter a problem related to rapid pressure rise. All engines, more particularly, large engines have a restriction on the pressure rise rate. This is because high pressure rise rates can cause vibration and excessive loads on the reciprocating components.

Figures 7.5 and 7.6 show the pressure - crank angle data obtained on an engine - 8 cylinder, 4 stroke, 1000 rpm, turbo-supercharged with inter-cooler with CR = 12 with a total swept volume of the cylinders of 127 liters and power output of 1768 kWe with furnace oil; the specific fuel consumption is 200 to 250 g/kWh at loads between 25 to 100 % with the minimum sfc at 50 % load. The data on all the cylinders are shown in the plots. In diesel mode of operation, the pressure achieved goes up to 80 atm and the maximum pressure rise rate of 2 atm/°crank angle. In dual-fuel mode, it is expected that the pressure and pressure rise rate go up and the pressure rise rate would be expected to be limited to 3 atm/°crank angle. However, the pressure achieved goes up to 100 atm and the maximum pressure rise rate up to 6 atm/°crank angle in a few cylinders. The asymmetric loads occurring over 3 to 4 ms can cause significant vibration apart from larger piston loading. Avoidance may call for change in liquid fuel injection timing, by retarding it by a few degrees, reducing the temperature of the incoming fluid, by reducing the temperature of the gas entering the cylinders from the aftercooler. or reduced compression ratio or a suitable combination depending on the engine.

7.2.1 Efficiency and energy distribution

The overall performance of engines of various capacities operating with fossil fuels and the performance with dual-fuel mode including emissions are described at select power levels in Table 7.2. This table has been composed from realistic data on specific engines and literature (see *www.dieselserviceandsupply.com*). There are several interesting aspects set out in this table.

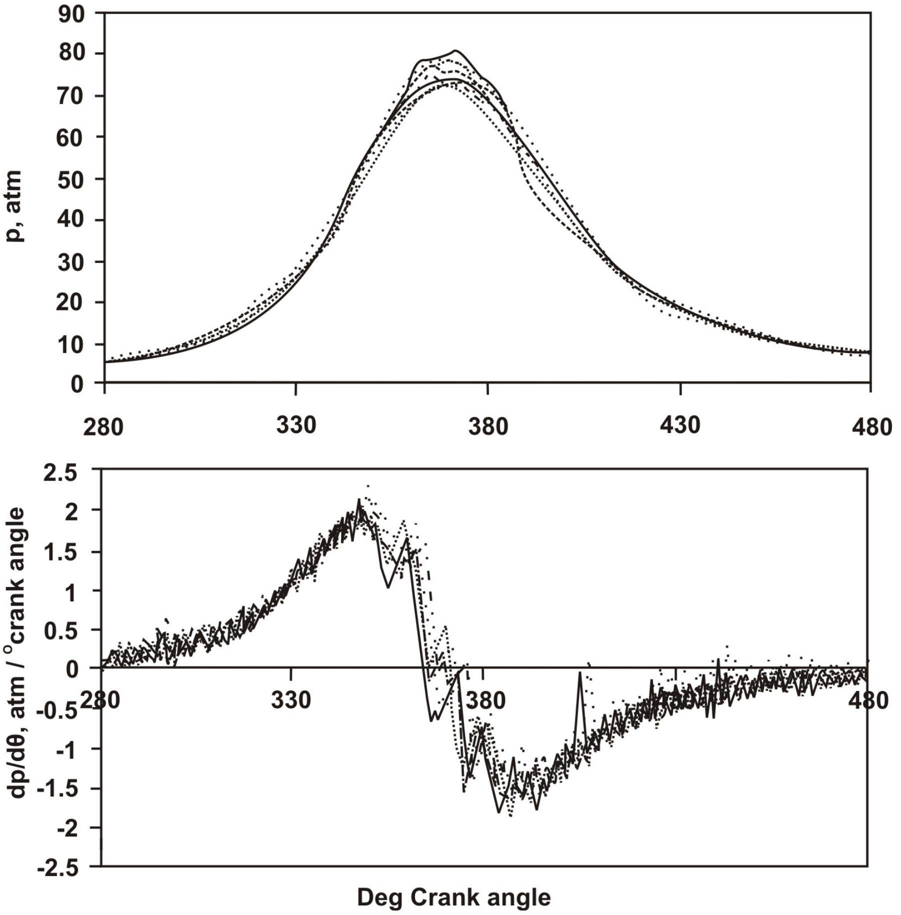

Figure 7.5: The combustion chamber pressure and the rate of pressure rise with crank angle on diesel mode

The diesel flow at no load goes towards maintaining the engine by overcoming the frictional power and associated cooling; of course, there is the inevitable exhaust heat loss. This is not a small fraction at low power levels. At 3.7 kWe, the loss is 23.2 %. It goes down to around 6 - 8 % at large capacities. Efficiency which is output/input is 0 since no useful power is delivered by the engine. As the output increases the efficiency also increases - to 17 % at 3.7 kWe up to 40 % at 2 MWe. The energy flow into cooling water and in the exhaust work out to 60 % at smaller power levels going down to 54 % at large power levels. The efficient high pressure turbo-superchargers extract heat from the exhaust of the engines to levels where the exhaust temperatures are 250 to 275°C where as in medium power engines it goes up to 400°C. The efficiency in dual-fuel mode are calculated with data on diesel replacement of 80 % and that the biomass consumed for this is at 0.8 kg/kWh up to 100 kWe. At higher power levels reduced amount of wood is assumed as shown in Table 7.2. The dual-fuel mode efficiency is much smaller than diesel-alone case. However, the principal point about the dual-fuel operation is the reduction in the amount of diesel used. At large power levels, the actual magnitude of diesel saved is very significant. This will be the driving factor for the use of dual-fuel operation in situations where diesel engines have already been in place or set up for other reasons.

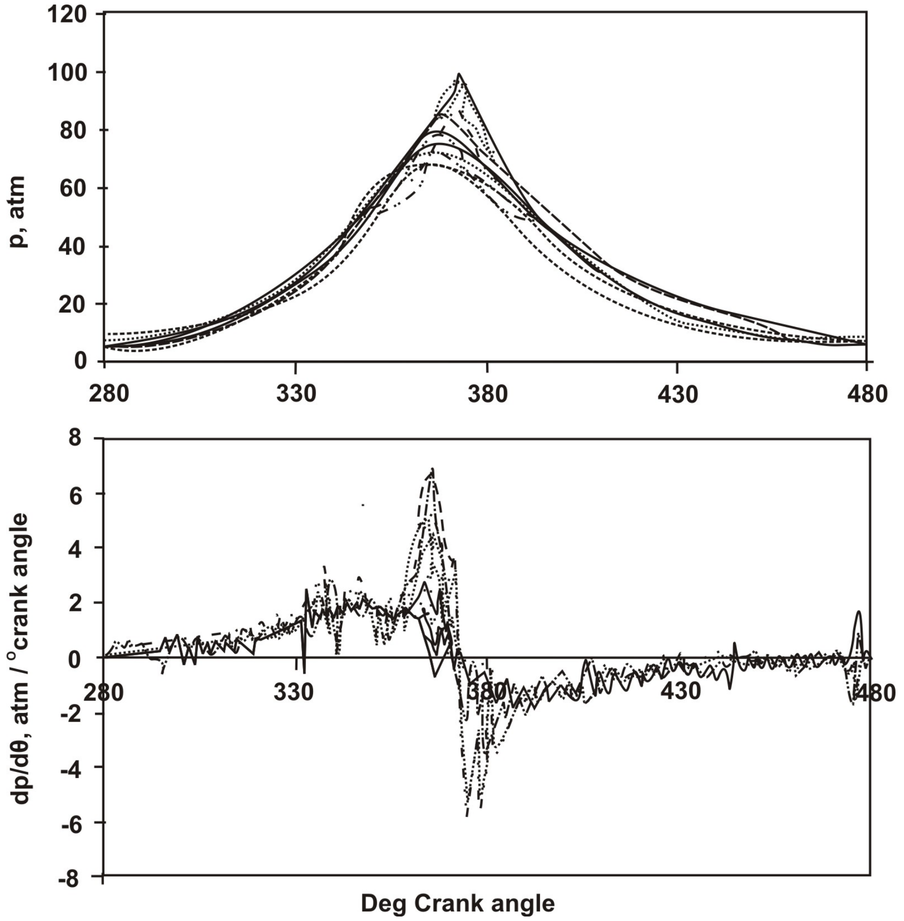

Figure 7.6: The combustion chamber pressure and rate of pressure rise with crank angle in dual-fuel mode

Table 7.2: Diesel consumption, energy distribution, and efficiencies in diesel-alone and dual-fuel mode; diesel calorific value = 43 MJ/kg; ; f.l = full load

Item Power, kWe ⇒	3.7	20	100	500	1000	2000	Unit
Operating rotational speed	1500	1500	1500	1500	1000	1000	rpm
Diesel (full flow)	1.85	7.1	26	120	217	419	kg/h
Diesel (no load)	0.45	1.6	7	21	23	25	kg/h
Energy at full load (f.l)	22	84	330	1430	2600	5000	kWth
Energy (f.l) into cooling water	6.6	24	90	400	700	1350	kWth
Energy in the exhaust	6.6	24	93	380	680	1350	kWth
Energy into friction + others	5.1	16	47	150	220	300	kWth
100 × (friction +losses)/input	23.2	19	14	11	8.5	6	%
Efficiency at full load	17	24	30	35	38.5	40	%
Sun-dry wood/energy	1.2	0.8	0.8	0.7	0.65	0.65	kg/kWh
Sun-dry wood at 80 % DR (f.l)	3.7	16	80	350	650	1300	kg/h
Diesel flow at 80 % DR. (f.l)	0.37	1.4	5.2	24	43.4	84	kg/h
Eff in dual-fuel mode	15	22.7	24	27.1	29.3	29.5	%

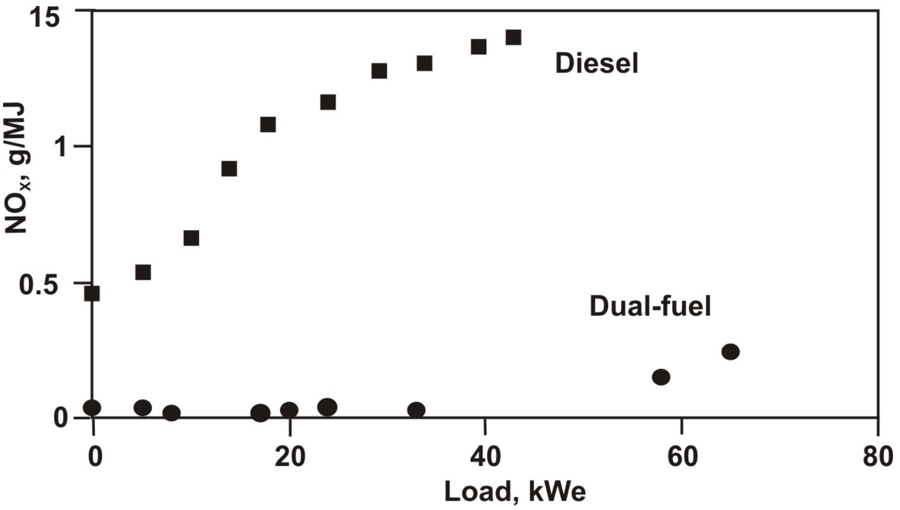

Figure 7.7: The variation of NO_x with load in diesel and dual-fuel mode

Table 7.3: Summary of emissions in diesel engines on Leyland and Kirlosker engines; For Leyland engines 65 kWe and for Kirlosker engine 40 kWe are taken as reference for 100 % load

Engine	Load %	Mode	NO_x g/MJ	CO g/MJ	HC g/MJ	SO_2 g/MJ
Leyland	50	Diesel	1.3	-	-	-
	100	Diesel	1.5	0.9	-	-
Kirlosker	50	Diesel	1.8	1.8	0.33	0.07
	100	Diesel	2.0	0.9	0.33	0.06
Leyland	50	Dual-fuel	0.05	-	-	-
	100	Dual-fuel	0.2	3.3	-	-
Kirlosker	50	Dual-fuel	1.1	3.6	0.45	0.03
	100	Dual-fuel	1.1	2.6	0.35	0.03

7.2.2 Emissions

In so far as the emissions in dual-fuel mode are concerned, the unburnt hydrocarbon (soot) content in the exhaust reduces significantly though the results of Uma et al (2004) seem different. Measured NO_x values with output is shown in Fig. 7.7. Levels of NO_x in dual-fuel mode also come down because peak temperatures are lower. The CO fraction in the exhaust is more in dual-fuel mode because the gas has a large fraction of CO that is quite slow to convert. A summary of the emissions obtained by Sridhar et al (2005) and Uma et al (2004) is set out in Table 7.3. The emissions of hydrocarbons (HC) and SO_2 have not been reported by Sridhar et al (2005). The measurements of Uma et al are generally higher than of Sridhar et al, though broadly they agree trend-wise. Clearly, the emissions of CO are to be a matter of concern and can be resolved through the use of a catalytic exhaust device. The significant emissions of HC in dual-fuel mode in the experiments of Uma et al are not easy to explain. The lower emissions of SO_2 have been explained as due to lower input of sulfur, as most biomass has little sulfur. In India, there are no stringent demands on emissions for such engines perhaps due to the fact that these engines operate in a widely distributed mode. In any case, diesel engine power generation is not practised as much as in the past as it is far too expensive. Larger power engines have associated emission control devices even for diesel operation and hence the aspect of emissions becoming an issue in power generation appears remote.

Table 7.4: Combustion properties of natural gas and producer gas

Property	Natural gas	Producer gas
Composition	CH_4 largely	19 - 21 CO, 18 - 20 H_2 1 - 1.5 CH_4 10 - 12 CO_2, 2 H_2O, Rest N_2, all in %
Density	0.65	1.0 - 1.05 kg/m^3
Stoichiometric air-to-fuel	17	1.2 - 1.4 (by weight)
Calorific value, fuel basis	50	4.9 MJ/kg
Energy/(fuel+ stoich air)	2.8	2.1 ± 0.1 MJ/kg
T_f of fuel with air	2250	1900 - 2100 K
Burning velocity$]_{stoich}$	0.36	0.4 to 0.5 m/s

7.3 Operation with Gas engines

The operation with gas engines differs from that with diesel engines much as it would happen with gasoline engines vis-a-vis diesel engines. While ignition occurs in diesel engines because of compression, ignition in gasoline engines occurs because of spark. This is because if the mixture is pressurized to as high levels as it happens in diesel engines, there will be "knocking" – sharp pressure rise leading to distinct and sharp sound. If the compression ratio is limited then no ignition is possible unless it is sparked. Thus with gas engines as well, one has to use lower compression ratio – 8 to 12 (instead of 15 to 20 as in the case of diesel engines) and a spark. Injection timing in a diesel engine is replaced by spark timing. One therefore needs a high voltage sparking source for this purpose.

As distinct from a diesel engine, one ingests a gas-air mixture into a gas engine. The mixture ratio and the flow need to be controlled. The mixture ratio is controlled by a carburetor and the flow rate is managed by a valve that acts as a controllable resistance through which flow enters the engine. Gas engines based on natural gas and biogas (or land-fill gas) have been around for a much longer time. Natural gas based engines have been used for power generation at hundreds of MWe based on gas turbine engines and up to tens of MWe based on reciprocating engines. The basic frame is usually the same as a diesel engine. Other components like carburetor and ignition system including electronic control are special fitments for natural gas operation. These reciprocating engines use a CR typically of 8 to 10 and a carburetor for mixing fuel and air at air-to-fuel gas ratios of 10:1. The same elements that are used on natural gas are also satisfactory for operating on biogas. The only additional element that comes in with biogas that may have hydrogen sulfide (H_2S) would be a scrubber for removing this offensive component.

The reference for producer gas engine is natural gas engine since any adaptation for producer gas operation can arise out of natural gas engine. Producer gas differs from natural gas in terms of combustion properties significantly. These are set out in Table 7.4. It is to be understood that while both gas compositions can vary, the changes that occur in natural gas occur over very long times and hence do not matter. The composition of producer gas can change due to bed movements occasionally over the scale of minutes. Producer gas is usually treated as a low calorific value gas. This is true, but appears exaggerated if the numbers on energy of the fuels seen in Table 7.4 are understood naively. The correct way of looking at this issue is on the basis of the mixture, because this is what that enters the combustion space of the cylinder. Hence, it is important to look at the energy per unit mixture. On this basis, the difference is not so significant. It is also important to note that on the basis of mixture, the volumetric and mass basis are the same for CH_4 because the mixture is dominated by air (fuel constitutes only 5 % of the mixture). A second factor against producer gas is the change of molecules when one moves from reactants to products. For this, we write the stoichiometric combustion equation for natural gas and producer gas.

$$CH_4 + 2\ O_2 + 2 \times 3.76\ N_2 \rightarrow CO_2 + 2\ H_2O + 2 \times 3.76\ N_2$$
$$10.52 \text{ molecules} \rightarrow 10.52 \text{ molecules}$$
$$0.2(CO + H_2) + 0.01CH_4 + 0.22\ O_2 + 0.22 \times 3.76\ N_2 + 0.1\ CO_2 + 0.02\ H_2O \rightarrow 0.31\ CO_2 + 0.24\ H_2O + 0.22 \times 3.76\ N_2$$
$$1.5772 \text{ molecules} \rightarrow 1.3772 \text{ molecules}$$

Thus one notices that when CH_4 burns the number of molecules does not change when we move from reactants to products, but with producer gas it decreases by 13 %. This change will contribute to the reduction in the achieved pressure inside the chamber. Reduced calorific value of producer gas results in lower flame temperature of producer gas - air mixture compared to natural gas-air mixture. A third factor in the case of turbo-supercharged engines is the fact that the turbine-compressor is designed for operation with natural gas related parameters. For producer gas related parameters that get affected by the two factors noted above, the input conditions are non-optimal and this results in lower pressure rise across the compressor of the turbo-supercharger. These issues demand that the best performance of an engine can be extracted when it is operated close to the nominal conditions. A gasifier that provides better composition reduces the impact of the factors noted above.

Going back to Table 7.4, the burning velocity (or flame speed) is the propagational speed of a premixed gas-air mixture, a fundamental property of gaseous mixtures as it reflects the chemical reactivity of the mixture. It is a function of the mixture ratio. It is a subject well studied in combustion literature (see references at the end of chapter 4). It is important to understand the propagational properties in the case of reciprocating engines because the phenomenology is related to premixed flame propagation in every cycle (it is not so in a gas turbine that has continuous diffusive combustion process). While hydrocarbons have received considerable attention, little attention has been paid to producer gas. This is because producer gas generation depends on the gasifier design and the need to run reciprocating gas engine. Considerable work was done on these aspects at the laboratory. Experimental studies by Kanitkar et al (1993) and computational studies on flame propagation by Chakravarthy et al (1993) have provided information on the propagational speeds as well as limits of propagation. Figure 7.8 shows the results of flame speeds with mixture ratio and equivalence ratio.

The flame speeds have some scatter partly because the composition was varying (typically ± 1 % in the larger reactive components) over the experimental duration. The maximum speed is about 50 cm/s, larger than for methane which is 36 cm/s. The problem of flame speed with producer gas is that it has two important components - H_2 and CO which have widely different flame speeds; 2 -3 m/s for H_2 and 0.15 - 0.3 m/s for CO. CO is a very slow in reactions and H_2 is very fast. The presence of an additional hydrogen content will improve the flame speeds significantly. The results shown in Table 7.4 indicate that stoichiometric A/F is 1.2 and the limits of propagation in terms of A/F are 0.7 - 0.8 (rich) and 2.8 - 3.0 (lean); the lean range is much wider than the rich range. The limit flame speed is between 6 and 10 cm/s for both rich and lean limits. Schneider (see the reference cited with Hardin et al, 2003) of Jenbacher has provided the flame speed of producer gas. The flame speeds are much lower than those noted above and seem close to that of CO. This does not appear proper considering a significant fraction of fast burning hydrogen in the mixture. Calculations made to obtain the sensitivity with hydrogen showed that every additional percent of hydrogen will enhance the flame speed by 7%. Perhaps, the mixtures used by them in the calculation had lower fractions of hydrogen.

In engine operating conditions, the starting conditions for the flame propagation will be at much higher initial temperature and pressure depending on the spark timing on the engine

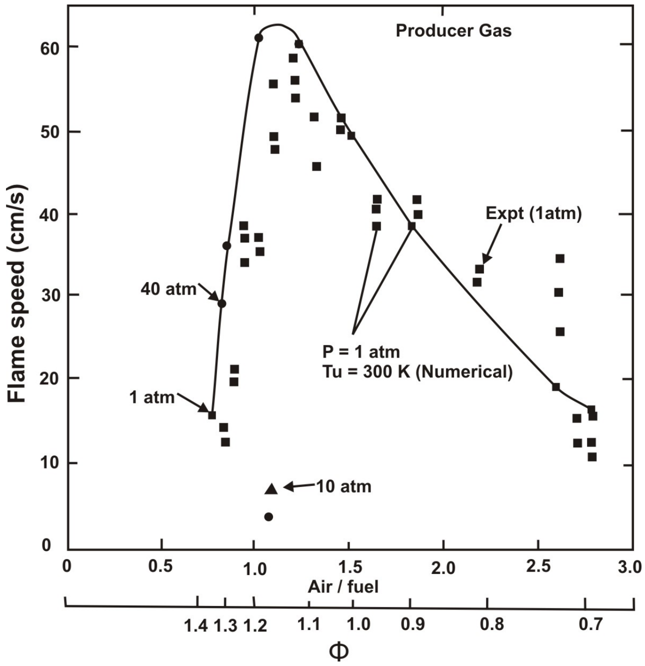

Figure 7.8: Burning velocity of producer gas as a function of Air-to-fuel ratio (and equivelence ratio) - experiments and computations, source: Kanitkar et al, 1993 and Chakavarthy et al, 1993

Table 7.5: Flame speed as a function of temperature, pressure and residual gas fraction (rgf), drawn from Sridhar, 2003

Pressure, atm	20	20	20	40	40	40
Residual gas fraction (rgf) %	0	5	10	0	5	10
Initial temperature, K	876	876	876	1028	1028	1028
Flame temperature. K	2330	2275	2200	2450	2395	2345
Flame speed, m/s	2.2	2.0	1.7	2.6	2.3	1.9

(that is typically 10 to 25° before top dead center) and the residual gases present in the combustion chamber after the exhaust stroke. Typical values of residual gas fraction are about 0.05 – 0.12 for most engines. The decrease in temperature with residual gas fraction is the effect of dilution and increased pressure leads to higher flame temperature because of reduced dissociation. The flame speeds are in the range of 1.7 to 2.6 m/s. Sridhar (2003) has made calculations accounting for these effects and typical results are set out in Table 7.5. It is important to understand these results in conjunction with the combustion behavior and modeling the processes inside the engine that typically starts with laminar flow propagation near the sparking location, but transitions to turbulent combustion. The interaction between turbulence and combustion is complex and attempts to understand are continuing over a long time (Gatowski et al, 1984; Arcoumanis et al, 1987; Heywood, 1988) just as well as the attempts to perform computer simulations of the flow using reactive flow computational fluid dynamics (see for instance, Jennings, 1992). Most of the work is connected with fossil fuels. Research to address the questions on producer gas using both experimental tools, one-dimensional and full flow simulations have been performed systematically at the laboratory at IISc (Sridhar et al, 2001, 2002, 2004; Sridhar, 2003).

From the point of view of development as well as research, one of the key elements required was the carburetor that can maintain a desired air-to-fuel ratio over a range of loads. Figure 7.9 shows the elements of the carburetor. The circuit consists of the gas line from the blower that

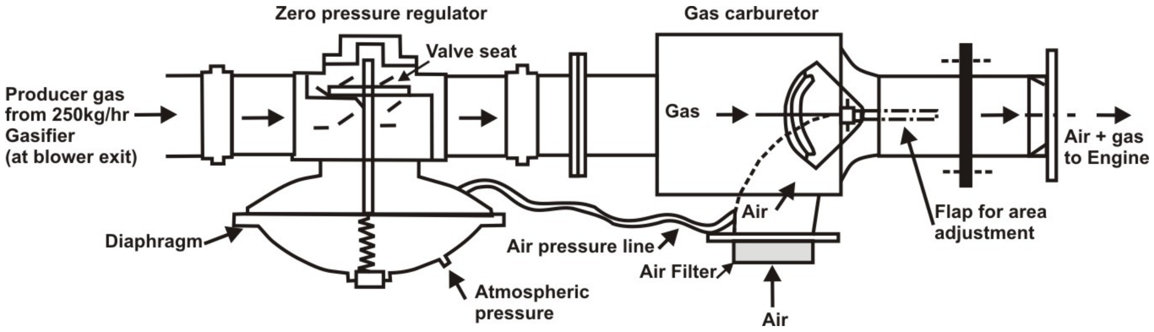

Figure 7.9: The schematic of the gas carburetor

maintains a pressure connected to a zero-pressure regulator and then a line that draws the gas and air into a duct downstream with a flap control. The zero-pressure regulator maintains the pressure in the gas line same as in the air line at varying demands of the engine. This process ensures that the relative flow rates are maintained at varying total throughputs. By positioning the flapper control differently, one can get a different ratio of air-to-gas flow. Experiments have been conducted for ensuring that the air-to-fuel ratio is near constant over a wide load range. One of the key issues in seeking a good carburetor lies in controlling the emissions. As was indicated in chapter 4, section 4.14, one needs to control the A/F so that the emissions of CO are properly controlled. Obtaining high efficiencies will demand that A/F is retained close to stoichiometry, minimizing CO emissions requires that excess air be provided. Thus the equivalence ratio is held on the lean side (ϕ = 0.95). The carburetor precedes the electronic governor that is a standard commercial item on all gas engines. One of the other commercially available systems used for feed back control to maintain a certain oxygen fraction in the exhaust would be a Lamda sensor whose output depends on the difference between the oxygen level in the exhaust and the ambient. This output can be used to modulate the flap control on the carburetor or the fuel alone as the designer wishes. The design elements based on flapper control and pressure regulator are deployed for the wide range of power levels - a few kWe to 1.5 MWe.

One of the questions that has not been adequately resolved in respect of compression ratio (CR) is whether engines can be operated on producer gas satisfactorily at higher CRs. This is because it is normally understood that the power obtained by operating on producer gas in known gasoline engines or more appropriately, natural gas engines would be much lower (Kaupp and Goss, 1981; FAO, 1986). The typical CRs at which these engines operate are about 8 for gasoline engines and about 10 for natural gas engines. Specific designs have raised the upper limit of CR to 12. Thus a question that needs to be answered is whether gas engines can operate on producer gas at CR's beyond 12. In attempting to answer this question, the spark timing becomes an inevitable parameter. Thus one has to seek regimes of good performance in the CR – spark advance domain. The gasifier-engine set-up along with an engine with measurement scheme is shown in Figure 7.10.

The engine used was a Kirlosker RB 33 engine coupled to a 25 kVA alternator (87 % efficiency) of an in-line, 3-cylinder, 4-stroke, naturally aspirated configuration operating at 1500 rpm with a swept volume of 1.1 liter, a CR = 17 and a rated output of 24 kWe on diesel, The specific fuel consumption on diesel at nominal rating is 285 g/kWh. The air-to-fuel ratio at nominal load is 21. The cylinder head has a centrally located injector converted to accept the spark-plug and the engine has a bowl-in-piston. The gasifier was operated on sun-dry wood pieces and the measured gas composition showed CO and H_2 of 19 ± 1 %, CH_4 = 1.5 to 2 %, CO_2 of 12 ± 1 %

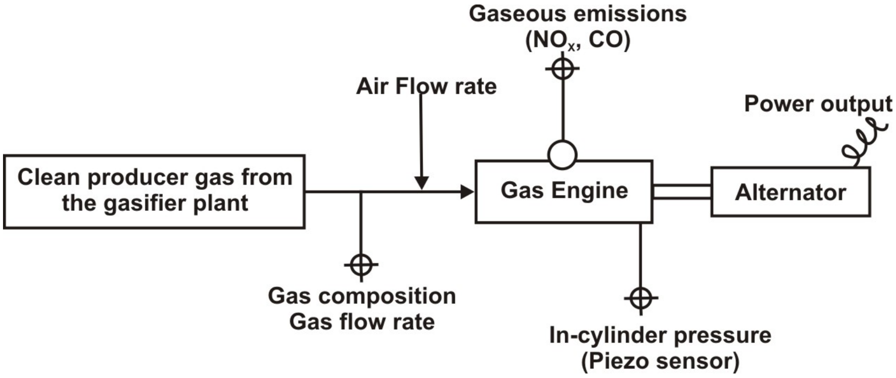

Figure 7.10: The schematic of the gasifier-engine set-up for making measurements of gas composition, in-cylinder pressure with crank angle and power output for various CR and ignition

and the rest nitrogen. The results of the in-cylinder pressures are shown in Fig. 7.11 for CR = 11.5, 14.5 and 17. The data are shown for several ignition advance values. The point to notice in the diagrams is that the pressure varies smoothly through the cycle. For all ignition advance values larger than 12°CA, the variation is as smooth at CR = 17 as it is for CR = 11.5. There are two additional aspects associated with the plots. The pressure rise rate in a few cases, at ignition advance of 12°CA, in particular shows a value of 4 atm/crank angle. This is perhaps beyond the acceptability limit from the viewpoint of continuous safe use, particularly for larger engines. The output is an integral of the difference between the chamber pressure - crank angle diagram and the motoring curve over the cycle. The output of the engine-alternator is shown as a function of ignition advance for various CRs in Fig. 7.12. As is clear from the composite plot, higher levels of output are obtained at retarded ignition advance. At each compression ratio there is a peak. Typical values of advance as indicated by this diagram are 12, 14-15, 16 - 18° for CR = 17, 14.5, 13.5 and 11.5 respectively. These values are to be considered in conjunction with pressure rise rate. The limitation of 3 atm/°CA implies most of the optimums except for CR = 17 holds good. Perhaps, a uniform value close to 15° should be satisfactory for all CR $>$ 13. The results need to be reviewed for large capacity engines with turbosupercharger of CR $>$ 1.5.

The gas-to-electricity efficiencies are 30, 29, 29, 27.5 % for CR of 17, 14.5, 13.5 and 11.5 respectively. Thus there is an increment of 2.5 % in efficiency with increased CR. These values can be converted to biomass-to-electricity efficiencies by multiplying them with gasification efficiency that will be typically around 75 % with sun-dry biomass. This implies biomass-to-electricity efficiencies of 22.5, 22, 22 and 21 % respectively. These translate to 1, 1.1, 1.1, 1.2 kg/kWh of sundry biomass with ash content of about 1 %.

7.4 Performance on lubrication

The lubricating oil is drawn into the cylinder along the walls to provide lubrication when piston rings move through the cylinder. The flowing lubricant comes into contact with the burnt gas or residuals near the wall. These contain complex compounds that react with the lubricant to degrade it. Further, if the gas contains “tar” part of it either directly or in complex reacted form will also appear near the wall due to the fluid dynamics inside the cylinder. The tars contain acids that will react with the chemicals in the lubricant in addition degrading it. The combined processes cause degradation whose observable effect would be reduced viscosity that

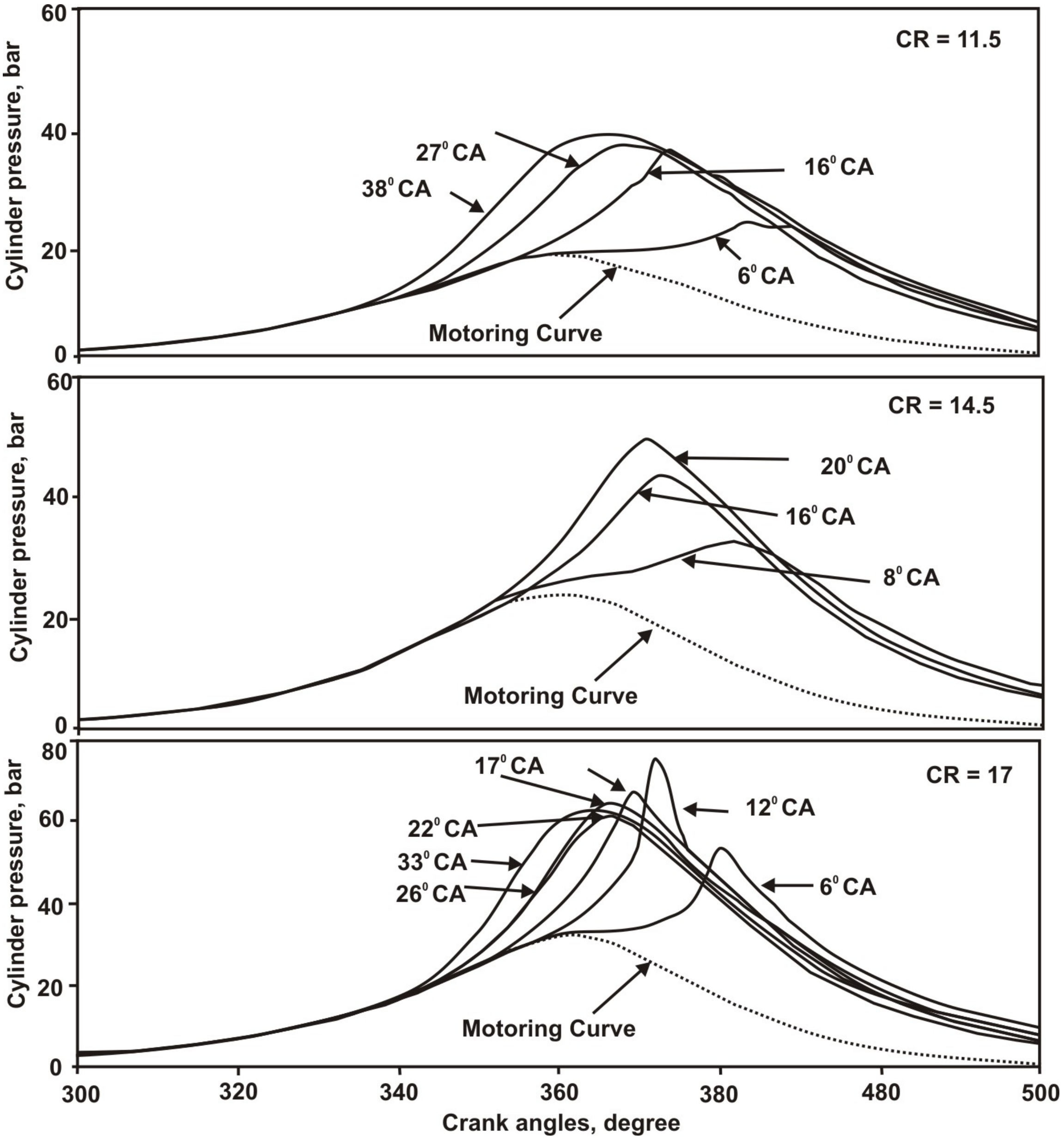

Figure 7.11: The measured chamber pressue - crank angle diagrams for CR = 11.5 (top), 14.5 (middle) and 17 (below); the data are averaged over 30 consecutive cycles

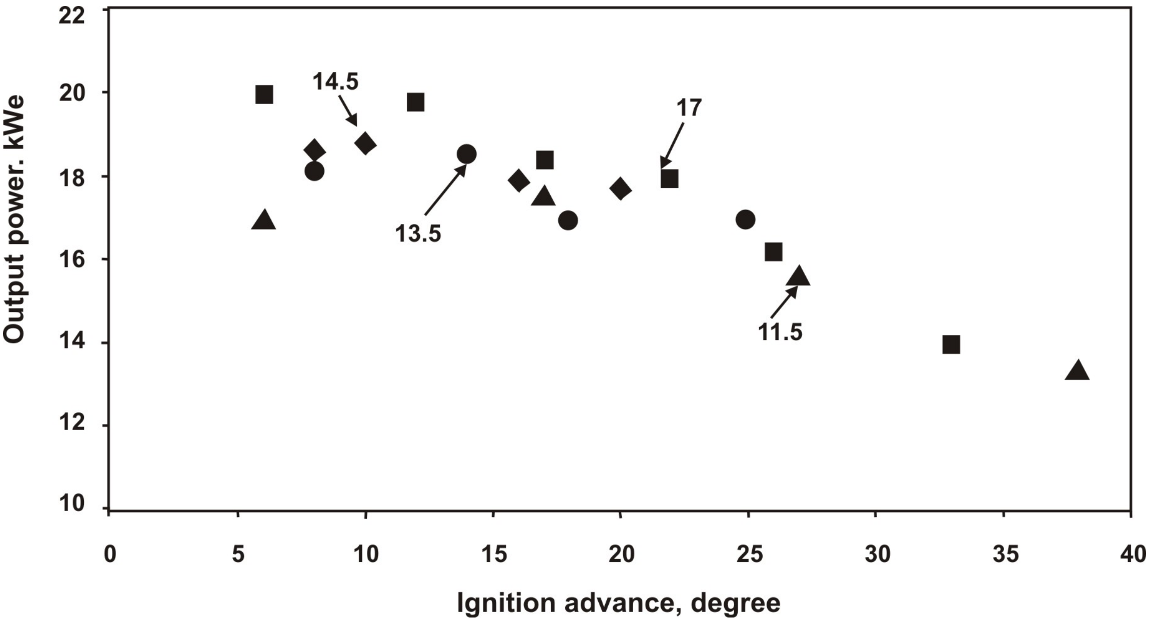

Figure 7.12: The output as a function of ignition advance for various compression ratios

Table 7.6: The lubricant's test and analysis over 500 hours of test, after various intervals

Parameter	specs	186 hrs	300 hrs	400 hrs	500 hrs
Flash point,COC, °C	230	220	220	220	220
Insolubles, pentane, % wt		0.14	0.07	0.26	0.09
Insolubles, toulene, % wt		0.06	0.05	0.17	0.07
Viscosity, cSt at 40°C	113.9	103.0	104.5	99.2	99.2
Viscosity, cSt at 100°	14.7	13.0	13.4	12.5	12.6
Nitration. abs cm^{-1}		7	18	39	49
Oxidation, abs cm^{-1}		12	20	43	41
TAN, mg KOH/g		2.1	2.1	3.0	3.8
TBN, mg KOH/g	5.68	14.4	3.9	4.1	3.8
Viscosity index	136	120	126	121	122
Water, % wt		0	0	0	

will prevent the functioning of the lubricant. Consequently, the lubricants are tested for the degradation in quality on a periodic basis - one in 250/500 hours of operation. The report in a 500 hours operation of a 6 B engine (Cummins) is presented in Table 7.6. The more important of the results are related to Total Acid Number (TAN), Total Base Number (TBN), viscosity and the presence of water. On the basis of these numbers, doubtlessly, the lubricant has accumulated acids and bases whose neutralization is what is indicated by TAN and TBN. These levels of degradation are considered to be within limits. There are also wear of metals found in the lubricant - Iron, Silicon, Tin and copper all less than 150 ppm at the end of 500 hours that are considered reasonable.

7.5 Emissions

Since the gas that is delivered to the engine is "clean", the gaseous emissions of importance are CO, NO_x and SO_x. The results of the measurements of NO_x and CO are shown in Figure 7.13.

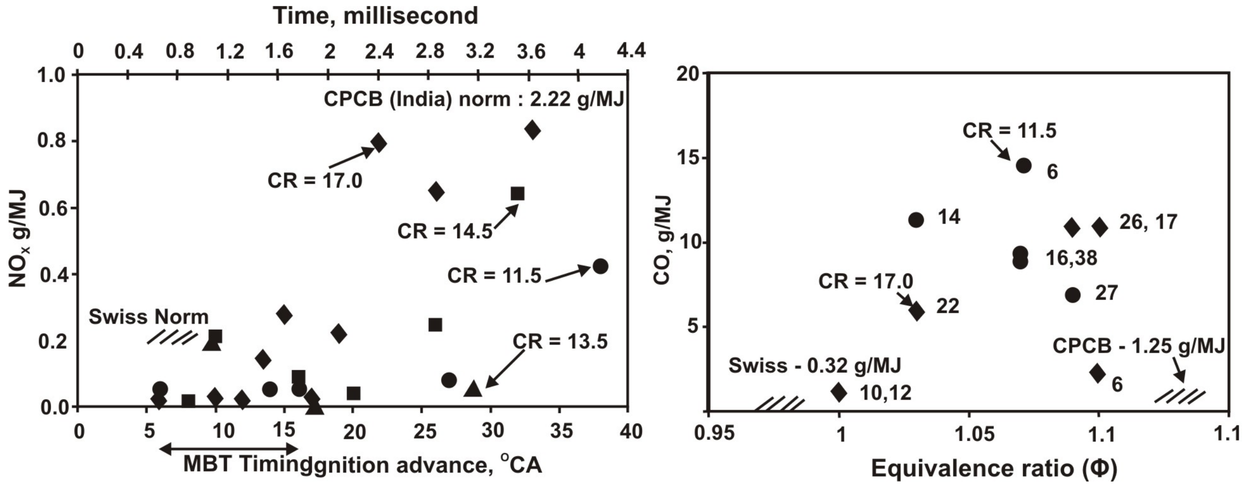

Figure 7.13: The variation of NO_x with ignition advance and CO with air-to-fuel ratio; the values indicated on the right side plot include the ignition advance in °CA and CR

It has been observed that the role played by flame temperature which plays such a significant in the generation of NO_x that NO_x generation is not high enough in producer-gas air mixtures to create problematic generation. It will be particularly insignificant if the residence time of the mixture in oxidizer rich zone is of a short duration. The left part of the figure shows that for the levels of ignition advance contemplated for compression ratios of 12 to 14, the NO_x levels are of the order of 70 mg/MJ, much lower than the limits on NO_x in most countries. It may be noted that the residence time computed for these cases using the ignition advance values shows that the emissions are low with residence times between 0,4 - 2 ms. The issue with CO is more complex. One of the reasons is that CO is a primary fuel here (compared to a fossil fuel where CO is generated in small amounts along the reaction pathway) and CO oxidation is known to be slow (see Chapter 4, section 4.14). The tests show a very large amount of CO going up to 10 g/MJ for a variety of parameters. Other tests (discussed below) have shown that these emissions are 0.5 to 2 g/MJ. These are above the norms in most countries. Hence an oxidation catalyzer is needed to reduce the emissions to the norms cleared by the authorities (in India, CPCB norms are 1.25 g/MJ and Swiss norms are 0.32 g/MJ). The sulfur dioxide emissions are also present to an extent of 10 - 30 mg/MJ. These arise from the engine operations and not as much from gasifiers.

7.6 Tests on small gas engines and load variations

Tests have been conducted on several engines from different engine companies – Cummins (capacities of 25, 55 and 80 kWe), Kirlosker oil engines Ltd (KOEL, 25 kWe) and Caterpiller engines (25 kWe). The conclusions that have been arrived at in the earlier sections are largely valid for most of these engines. These tests have shown steady performance with ignition advance of 14 to 16°. The biomass consumption with sun-dry biomass was 1 - 1.1 kg/kWh with all Cummins engines. With KOEL engine, the engine was operated at varying compression ratio - 12, 14 and 18. The performance at CR = 12 at an ignition advance of 16° gave an output of 21.5 kWe; at CR = 14 and at an ignition advance of 14°, an output of 23.5 kWe. At CR = 18, the engine operated well but the output dropped to 21.5 kWe at an optimum advance of 8°. The specific fuel consumption was obtained as 1.4 - 1.5 kg/kWh; this was related to an oversized radiator and it was estimated with appropriate radiator, the sfc would be restored to the values observed for Cummins engines. The experiments on Caterpiller engine that had a CR = 8.5 delivered 22.5 kWe on LPG with a specific fuel consumption of 0.34 kg LPG/kWh. This engine when operating on producer gas showed a peak delivered output of 15 kWe with biomass consumption of 1.5 kg/kWh. Obviously, if the CR was raised to 14, one would restore the output power and consequently, the biomass consumption per kWh.

The Cummins engine delivering a peak output of 27 kWe produced emissions of 0.6 to 1.3 g CO/MJ, 10 to 70 mg NO_x/MJ and 40 mg SO_2/MJ. The 55 kWe gas engine in Switzerland showed emissions of 0.9 g/MJ of CO and 140 mg/MJ of NO_x. The Caterpiller engine showed at 15 kWe emissions of 0.3 to 0.75 g CO/MJ and 50 to 70 mg NO_x/MJ. As indicated earlier, the emissions of NO_x are below the norms and those of CO beyond the norms. In one engine of Cummins 120 kWe system, it was found that the emissions were 0.4 to 0.5 g CO/MJ and 200 - 300 mg NO_x/MJ showing lower emissions of CO and higher emissions of NO_x. From these results it appears that the generation of these pollutants is a function of the geometry of the piston head, compression ratio, intake and exit opening/closing crank angles. Modeling tools might provide guidelines for design of systems to minimize the emission of CO in particular.

On these engines as well as larger engines fast load change tests were performed to determine the response of the engine to transition into the new steady state. These tests are unimportant in advanced countries in which the grid is functional all the time; even small engines can feed into the grid without the fear of being affected by the loss of grid. In India and many developing countries, this is not the case. Even when connected to the grid, the outages due to the loss of grid can occur 10 to 15 times a month on 11 kV electrical grid link and the associated safety of the equipment will be paramount. In fact, no operational license will be provided by the authorities until all the safety related equipment will be in place. Also the small engines ($\sim$ 250 kWe) may supply power to industries with several machines that may be turned on and off at odd times. The engine must be able to manage the loads and maintain the frequency.
For these reasons tests have been conducted to determine the way the system reacts when load changes are made suddenly, both up and down (ABETS, 2010). The systems used invariably an electronic governor and carburetor with pressure regulator of the type described earlier. Tests on all the engines showed that dumping about 25 % nominal load maintains the frequency with no perceptible change. Load changes up to 40 % take between 1.5 - 3 s for the system to recover to the new load with frequency traverse up to 2 Hz with loading up taking a smaller recovery time than dumping the load. Larger load changes take up to 10 s and these are undesirable. Specific tests done by Satake company (one of the licensees of IISc technology) at the university of Suaranaree in Thailand (see ABETS, 2010 for a full report by them) showed that for an engine that had mechanical governor, one should use at least 1.5 kPa gas pressure for helping the regulator to function fast and a electronically controlled blower to respond to the variations in the flow demand.

The system at Suranaree was used for long duration tests on rice husk briquettes. Chapter 6, section 6.12 presents some details of the gasification system. The operation of the gas engine on wood for initial tests was performed with an output of 80 kWe at a consumption rate of 1.1 kg/kWh. Figure 7.14 shows the rice husk briquettes (the spiral type) stored for gasification, the pieces of the briquettes loaded into the open top system and the gas engine. Also seen is the carburetor whose features were discussed earlier (Fig. 7.9). For operation with rice husk briquettes, the maximum engine load was restricted to about 72-74 kWe. The ash extraction rate was maintained at about 25 %. The specific biomass consumption was around 1.4 kg/kWh in the limited experience of 20 hours, the plant operation was found to be satisfactory. The ash conversion was nearly complete as the ash extraction at 25% was found satisfactory to maintain the steady operations. At the end of the trial, the pressure regulator and the engine's throttle

Figure 7.14: Experiments on gas engine working on the Japanese spiral rice husk briquettes

valve were opened and examined. No deposition was found and operations were concluded to be good. The plant has successfully completed over 150 hours of operation without any problems. Subsequently, the engine was run at full capacity of 78 to 89 kWe and the rice husk briquette consumption was 1.3 kg/kWh. After these tests were completed, it is being used for other research on precipitated silica from rice husk ash.

7.7 Large gas engines

It was mentioned in Chapter 6 that Imbert Company had established 3 × 430 kWe systems in Paraguay (Zerbin, 1983; FAO, 1986) This document has presented many technical details of the system that are very instructive. These engines obtained a performance of 1.2 kg/kWh with wood at 20 % moisture consistent with the results of the previous section. They have run for hundreds of thousand hours in an environment that cannot be considered very understanding. This must give reassurance to well informed people about gas engine based power generation at large power levels, but seems not to have had enough influence (descriptions in FAO, 1986, Reed and Das, 1988, or Stassen, 1995). In some way, many aspects had to be reinvented or at least reassured, perhaps with newer approaches.

Table 7.7: Projects, engines, and characteristics of gases used in the engines by Jenbacher engines Company, Austria; T-select - Thermoselect process for waste gasification; the numbers within brackets refer to the number of projects in these cases

Project (Nos)	Gas source	CO %	H_2 %	CO_2 %	N_2 %	CH_4 %	LCV MJ/nm^3
T-Select (9)	Waste Gasn.	20 - 40	35 - 40	25 - 35	2 - 5	-	5.4 - 7.2
Austria (3)	Chem. ind.	1.5	16 - 21	5	71- 76	1.5	1.8 - 3.6
Spain (2)	Coke gas	5	55	5	5	30	17.3
Spain (2)	Conv. gas	60 - 75	1	13.5	13	-	8.6
Harboore DK	Wood Gasn.	25 - 28	15 - 18	7 - 10	45 - 50	3 - 5	6.8
Gussing, Au	Wood Gasn.	24	40	23	3	10	9
Finland, DK	Wood Gasn.	18 - 20	15 - 18	12	50	2	6.1
Spietz, Ch	Wood Gasn.	18	15	12	53	2	4.5

The largest gas engine available in India today is Cummins engine GTA 1710G engine expected to deliver 250 kWe. This engine was used in building a 1 MWe power plant for grid synchronized application as a part of commercial demonstration and the performance monitored. Dasappa et al (2007) describe the details of the observations on the engines after 5000 hours of operation in a field location that uses 5 × 250 kWe gas engines with 2 × 850 kg/h gasification system using coconut shell for some periods and Prosopis Juliflora in other periods, the choice related to the procurement price of the fuel. The engine was stripped and all the components including valves, valve seatings, pistons and piston rings were examined and it was concluded that the wear that was found in various components was within the normal expectation in natural gas engines. One point to note is that a natural gas engine of the same frame would generate higher power and hence one can look upon this experience as being one with derating. In fact, the engine was capable of greater power output, but was restricted to this value by the cautious approach of Cummins, India.

The only other company in the World that has had a wide experience on using special gases in reciprocating engines is Jenbacher (Herdin et al, 2003 and Martin Scheider's presentation noted against this reference). Table 7.7 shows the details of projects, engines and gases used in these engines. In the above table, Techno-select is a special waste-to-energy project that does oxygen gasification and any nitrogen found in the gas is because of leakage of air into the system. The projects on coke gas and converter gas refer to steel industry. The project at Harboore, Denmark is based on an updraft gasifier. The project at Gussing is based on fluid bed gasification with steam. Here again, nitrogen is only because of leakage. The projects in Finland, Denmark and Switzerland are based on downdraft gasification. One of the very interesting aspects of Table 7.7 is that a variety of gases with H_2 content varying from 1 to 55 %, and CH_4 content up to 30 % have been handled in gas engines. The energy content of the gas varies widely from 1.8 to 17.3 MJ/nm^3. The nitrogen content in the gases in several cases is small. In these cases, the use of the gas for power generation appears sub-optimal, for as was explained earlier, what is important is the calorific value based on the gas mixture and not gas alone. Even if the gas is rich (meaning high calorific value), mixing it with air at substantial proportions averages out the differences in the actual energy input. For several cases considered above and the basic constituents, the calorific values based on the fuel in volume and mass units are all set out in Table 7.8. Even for the extreme cases of H_2 and CH_4, whose calorific values are very different from most other gases, volume or mass-wise, the values become not vastly different when the mixture is considered. This is very clear from the plot shown in Fig. 7.15. The large variation in the calorific value between different fuels when fuel gas is chosen as the basis is reduced significantly when the fuel-air mixture is chosen as the basis.

Table 7.8: The calorific value of the special gases in the earlier table on volumetric and mass basis LCV = Lower calorific value, Subscripts, f, m = fuel and mixture

Project	CO %	H_2 %	CO_2 %	N_2 %	CH_4 %	LCV_f MJ/nm^3	$\mathscr{M}_f$ -	LCV_f MJ/kg	LCV_m MJ/nm^3	LCV_m MJ/kg
T-Select	30	40	27	3	-	6.2	21.9	6.8	2.3	2.1
Austria	1.5	18	5	74	1.5	2.5	23.9	2.5	1.6	1.5
Spain	5	55	5	5	30	17.3	10.9	38.4	3.5	3.1
Spain	70	1	14	13	-	8.6	29.4	7.1	2.6	2.6
Harboore	25	15	7	48	5	6.8	24.6	6.7	2.7	2.5
Gussing	24	40	23	3	10	9	20.1	10.8	2.6	2.4
Fin, DK	20	15	12	51	2	6.1	25.8	5.7	2.8	2.7
Spietz,	18	15	12	53	2	4.5	25.8	4.2	2.1	2.0
H_2	0	100	0	0	0	10	2	120	4.7	3.4
CH_4	0	0	0	0	100	36.5	16	55	3.2	3.0
CO	100	0	0	0	0	12.7	28	11	3.2	3.2

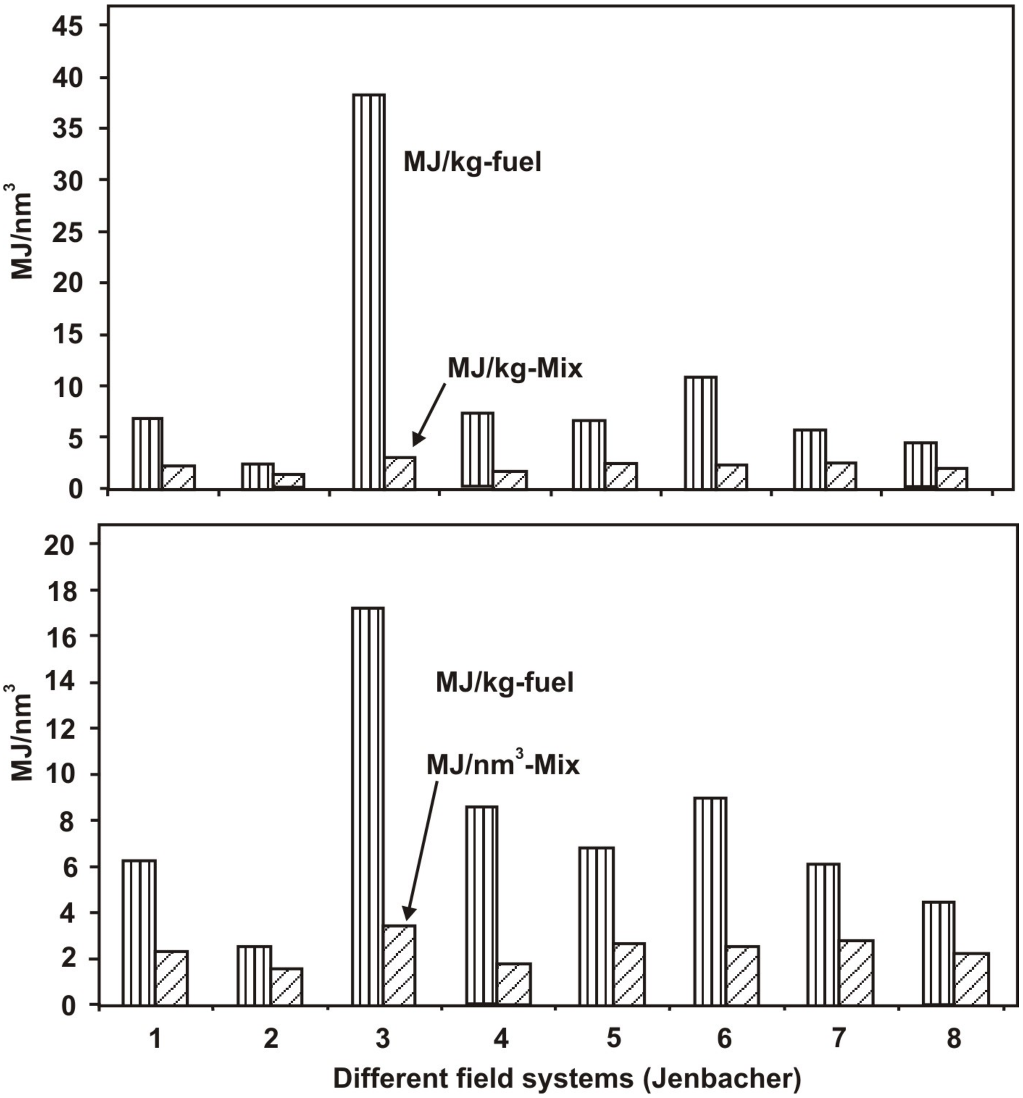

Figure 7.15: The bar-charts showing the energy in MJ/kg (above) and MJ/nm^3 (below) for the fuel and the mixture; data from Table 7.8

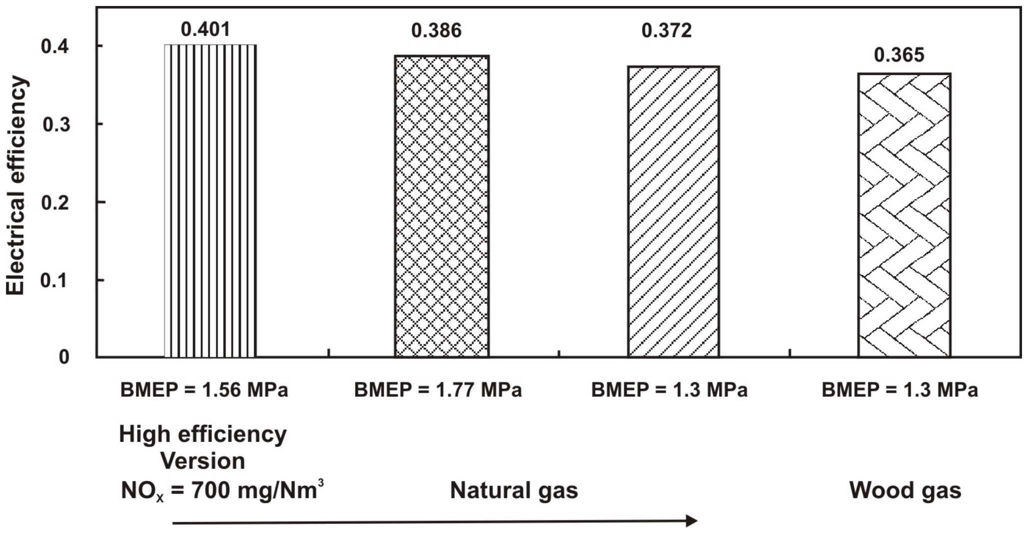

Figure 7.16: The improvement of overall fuel-to-electricity efficiencies through increase in BMEP by M/s Jenbacher engines

Large engines obtain high efficiencies by using turbo-superchargers and raising the brake mean effective pressure (BMEP). since the power out is directly related to it by Power = BMEP × (Swept volume of the cylinders) × (rps/2) where rps is the engine revolutions per second and the factor 2 appears here for the four-stroke engines that are considered here. Jenbacher engine have improved their producer gas engine efficiencies as shown by Herdin et al (2003) in Fig. 7.16. Increase in BMEP from about 13 atm to 17.5 atm raises the efficiency from 37.2 to 40 %. Producer gas operation at 13 atm shows an efficiency of 36.5 %. Cummins engines also have natural gas engines which operate at high BMEP. These have yet to be applied to producer gas. Thus much can be expected with high efficiency power generation if the engine manufacturers uprate their engines to operate at higher BMEP.

Many of the biomass gasification systems using Jenbacher engines (the last four systems in Table 7.7) have such poor raw gas quality in terms of tar and particulates that as “engines people” they have expressed serious concerns in terms of gas quality in their public presentations (Martin Scheider and Herdin et al, in Herdin et al, 2003). One would expect that downdraft gasification systems should have much less problems and those where re-burn strategy is practiced like the open-top re-burn gasifiers, the problem should remain virtually eliminated. In fact, in the operating experience on Cummins engines, no deposition of naphthalene has been seen and the distortion of the pressure regulator diaphragm occurred in two field systems that had operated for over a thousand hours satisfactorily. The observation similar to the top part of Fig. 7.17 was directly traced to the operation of the gasifiers with wet biomass (coconut shells drenched in rains during transport!) in the monsoon season. Whenever there was good control on the quality of biomass in terms of moisture and size, the operations have been smooth for several thousand hours.

7.8 Independent power plants (IPPs)

The previous chapter discussed the gasification aspects and the discussion in this chapter has been connected with the technical aspects of the power generation system. It would be useful to consider the combination of the two as an independent power plant. While there are a large

swell of the
diaphragm of the
pressure controller
due to condensates

first test phase Spiez

naphthalene crystals
gas pressure
control valve
naphthalenes > 1g/sm^3
LHV = 5.414 MJ/sm^3

Figure 7.17: The distortion of the diaphragm in a pressure regulator due to tar and the deposition of Naphthalene crystals in the pressure control valve of projects with Jenbacher engines

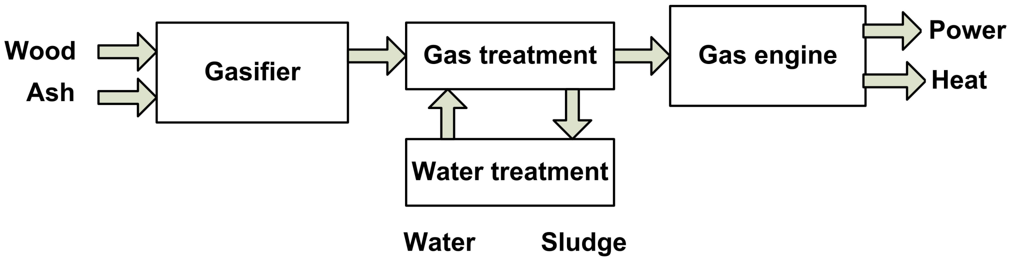

Figure 7.18: The gasification - power generation system schematic

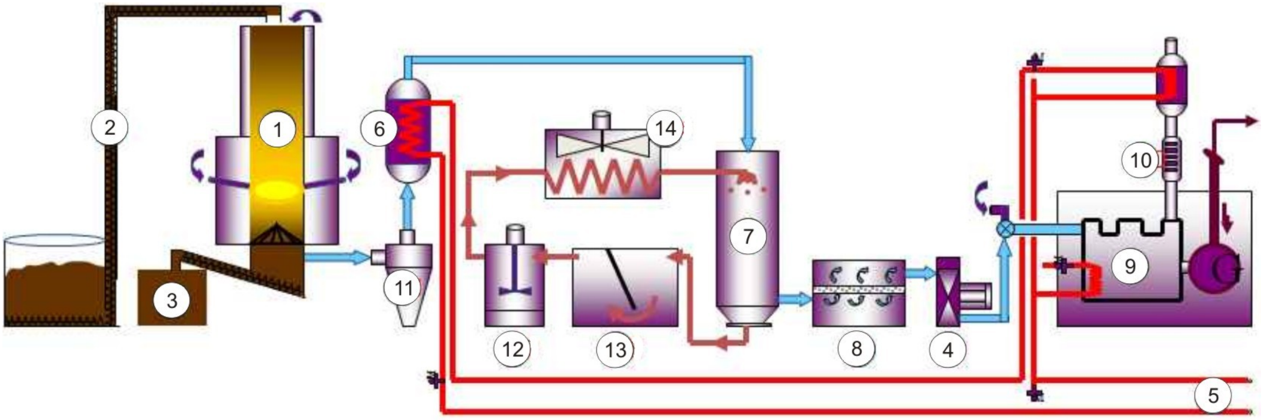

Figure 7.19: The elements of the gasification system and the engine in Switzerland; 1 = Reactor, 2 = Wood conveyor, 3 = Ash container, 4 = Blower, 5 = Water heating circuit, 6 = Heat exchanger, 7 = Scrubber, 8 = filter, 9 = Gas engine and generator, 10 = Catalyser, 11 = Cyclone, 12 = Flocculation tank, 13 = Decanter, 14 = Aircooler

number of such power plants in India and overseas with different technologies, only a few systems will be described here because of the availability of the details of operation. A 55 kWe system was established by a company called Xylowatt (Switzerland) based on IISc technology. The schematic of the total system is set out in Fig. 7.18. The full diagram of the system elements is presented in Fig. 7.19. As can be noted, the system has elements including the ash discharge and sludge collection which need to be examined before disposal as per Swiss norms. The gasification system is a 54 kg/h waste-wood-pieces based system. The entire system was instrumented and the information on the performance was collected and web-enabled for access from outside location. Wood chips are loaded on to a bin periodically. The system operated without any manpower support on-site. The control system logic would evaluate if there were emergencies and send a message to the mobile of the supervisor and shut down the system in a safe mode. This system operated for 500 hours. While the gas going into the engine in terms of composition is about the same as discussed in section 7.3, the particulate matter for the raw gas and the clean gas are presented in Fig. 6.24. It has already been noted there that the clean gas has 48 mg/nm^3 of particulate matter out of which 99 % is blow 2 μm. The system performed in uninterrupted manner after the initial settling period nearly continuously. The output would have minor fluctuations between 45 to 47 kWe. The energy distribution of the power plant is presented in Fig. 7.20. It is clear that the wood-to-electricity efficiency is 24 %. Other components of the heat distribution are evident in the diagram. Finally, the gaseous emissions from the engine are set out in Fig. 7.21. These emissions were obtained after establishing an oxidation catalyst at the exhaust. Otherwise the CO emission was 1800 mg/nm^3 at 5 % oxygen in the exhaust beyond the Swiss norm of 650 mg/nm^3. As can be noted

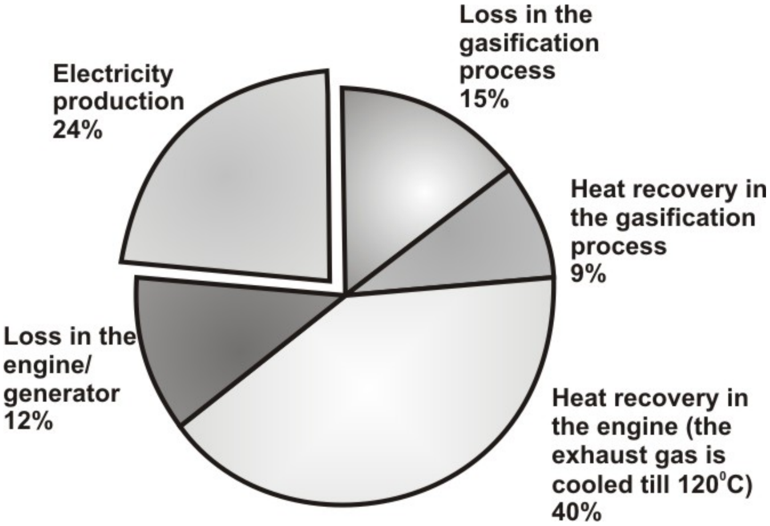

Figure 7.20: The energy distribution of the power plant

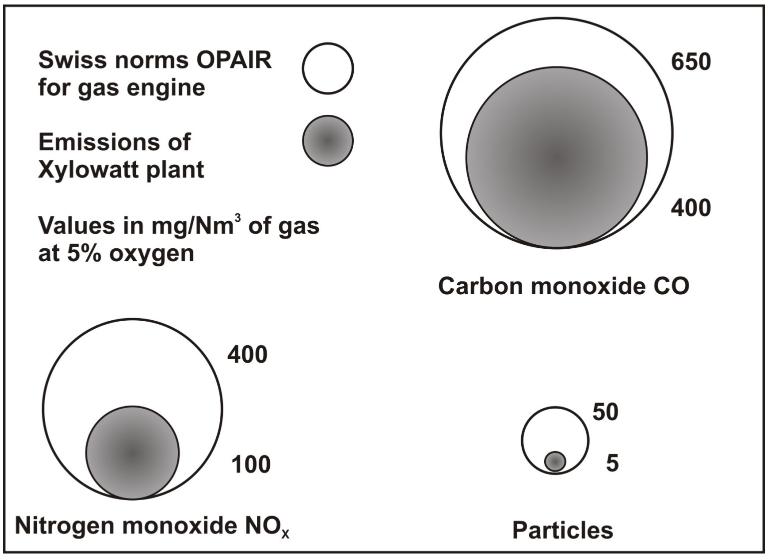

Figure 7.21: The emissions from the power plant

in the figure, the values are provided in terms of mg/nm^3 at 5 % oxygen in the exhaust. We should convert this to g/MJ. The relationship can be worked out as follows. The required g/MJ is set out as

g/MJ = g/nm^3 (f$_{ox}$) × [nm^3 (f$_{ox}$)/nm^3 (0)] [nm^3 (0)/kg (biomass)] [kg (biomass)/ MJ (biomass)]

$$\mathrm{g/MJ} = [\mathrm{g/nm^3 at} f_{ox}] \frac{1}{1 - f_{ox} + \frac{0.79}{0.21} f_{ox}} \frac{S+1}{\mathrm{LCV}} \tag{7.1}$$

where f$_{ox}$ is the fraction of oxygen in the exhaust (0.05 here), S is the stoichiometric ratio of biomass and LCV is the lower calorific value of biomass. The first term on the right hand side relates the total gas to gas without any oxygen, the next term relates this gas to the biomass that was responsible for the gas and the last term relates that to the energy in the biomass. For the values shown in Fig. 7.21, namely, 400 mg/nm^3 of CO, 100 mg of NO$_x$ and 5 mg of particulate matter all at 5 % oxygen, taking S = 5 and LCV as 15 MJ/kg we get the values in terms of mg/MJ units as 140 for CO, 35 for NO$_x$ and 1.7. These values are well within the norms prescribed for emissions.

Another plant of 450 kWe capacity has been built at Wila (Switzerland) using the IISc technology (Bossard, 2008). In India, a number of independent power plants at 250kWe, 1 MWe (5 x 250 kWe), 1.2 MWe (7 x 250 kWe) have been built and *they have operated for more than 10,000 to 50,000 hours*. The first 1 MWe system established in 2004 was the one that went through rigorous testing by a joint team of M/s Cummins, India and scientists from IISc. These results have been discussed in the earlier sections (see Sridhar et al, 2007 for more details). More IPPs at 1 - 1.5 MWe are currently under construction in India and Thailand.

7.9 Tri-generation possibilities

In Europe and the Americas, CHP - combined heat and power is a standard term in power generation systems. In tropical countries with average temperatures between 25 to 35°C, demand for heat is not as much. Even in colder areas, it is only for a short period that there is demand for heating. One needs to consider alternate approaches for multiple generation. Gasification systems promise at least tri-generation. The heat available at the exit of the reactor can partly be used to dry biomass when needed or for producing distilled water by evaporation and condensation or for vapor absorption systems for cold storage. The char extracted from the gasification system has a surface area in closed top designs of 100 m^2/g and about 450 to 550 m^2/g for open top reburn systems. The char at the lowest end can be used as biochar to improve the quality of the soil (Lehmann, 2009) and at the higher end directly as activated carbon for select applications; it could also become a feed stock for further activation. Open top systems could produce char output of 33 % and allow the dirty gas for steam power generation as well as for steam activation of the char. There will be heat at 400°C that will be available for applications cited above or others. Thus the generation of electricity, char and heat for other industrial uses are distinct possibilities some of which are already in practice.

7.10 Gas turbines

Producer gas can be used in gas turbines to generate electricity. Gas turbines operate generally on gaseous fuels like natural gas and liquid fuels like kerosene, alcohols, or diesel. Air from the ambient is drawn into the rotating compressor, compressed to the desired pressure which is typically 5 to 10 atm in the case of small power systems and delivered to the combustion chamber. Fuel is injected at high pressure into the combustion chamber. Natural gas is usually available at high pressure and does not require any compression. In some instances, the pressure is to be throttled down to levels at which it is to be delivered to the injection system of the gas turbine. The air-to-fuel ratio in all hydrocarbons is 15 and for alcohols around 6. This means that the fuel to be pumped even at stoichiometric conditions is about 7% of the air flow for hydrocarbons and about 16% for alcohols. Usually small gas turbine engines work at combustor outlet or turbine inlet temperatures of about 1000°C or so. This implies that the fuels to be pumped are at 3 - 4% for hydrocarbons and about 10 - 12% for alcohols. Thus even if the liquid fuels are to be compressed, the flow rates are relatively small and compression constitutes a small fraction of the energy produced. Nearly all the gas turbines are designed such that the fuel fraction is a small. If stationary applications can use the exhaust heat (that is not small) to recuperate the heat by passing the compressed air through the heat exchanger that passes on another side the hot gas, the amount of fuel needed for the operation will be even smaller. Typically, these correspond to fuel-to-electricity efficiencies of 30 %. The only problem with this approach is the life of the heat exchanger that needs to operate at reasonable pressures and high temperatures.

Use of producer gas has several issues. The air-to-fuel ratio is about 1.4. Capitalizing on recuperation will be essential if the system has to compete with reciprocating engine option in terms of efficiency. Even so, the air-to-fuel ratio will be about 6 – 10. This A/F is much beyond the lean flammability limit of producer gas. The feature that every gas turbine burns fuel and air at air-to-fuel ratios in the lean regime much beyond the flammability limit is well known. In this sense, both aspects are similar. The design of the combustion systems for creating conditions of correct mixture ratio for ignition and primary combustion could be different for hydrocarbons and producer gas. This will need that the combustion system be accessed and tested.

In so far as tests on small gas turbines are concerned there are only two studies – Sridhar et al (2007b) and Biomass Engineering ltd (2004). Sridhar et al conducted a study by building a high pressure gasifier for 5 atm whose design is the same as the classical ambient pressure gasifier, but modified to operate at higher pressure. The operation required air lock valves for feeding the biomass and extracting the char/ash. The system capacity was worked out as 75 kg/h. The inability to get a micro-turbine for testing from well established manufacturers forced the authors to obtain an auxiliary power unit of an aircraft from secondary sources. This engine system had an output of 32 kWe attached to a three-phase 40 kVA generator producing electricity at 208 V and 400 Hz. The engine rpm itself was 8000. The air mass flow rate was 675 kg/s and would be able to burn a maximum of 40 kg/h of kerosene in a reverse flow combustion system. Measurements using kerosene showed that the maximum output was 18 kWe with an sfc of 2 kg/kWh. Th engine operated in an open cycle mode - with no heat recuperation from the exhaust heat. In order to make modifications for the combustion system, it was dismantled and the ignition and combustion with producer gas were tested. This needed modifications. Figure 7.22 shows the reverse flow combustor that was tuned to operate for satisfactory ignition and combustion at air-to-gas flow rates of 6 to 8. The gas entry area that has a recirculation zone had to be altered to ensure smooth ignition and combustion. Even though these experiments were done with lower flow rates, fixing the problems of ignition/combustion in this manner was found adequate to operate the complete system at higher flow rates and higher pressures. The performance of the system is described in Table 7.9. The overall efficiencies achieved in this study was 2.5 % on kerosene and 1.6 % on biomass. Enhancement in the efficiency on

Table 7.9: Performance of the gas turbine on high pressure gasifier

Load kWe	p_c atm	gas flow rate, kg/s	Air flow rate, kg/s	A/F	rpm %	T_{exit} °C
7.9	1.7	0.11	0.65	5.9	96	451
10.1	1.7	0.094	0.65	6.9	98	477
11.4	1.7	0.12	0.65	5.6	96	470

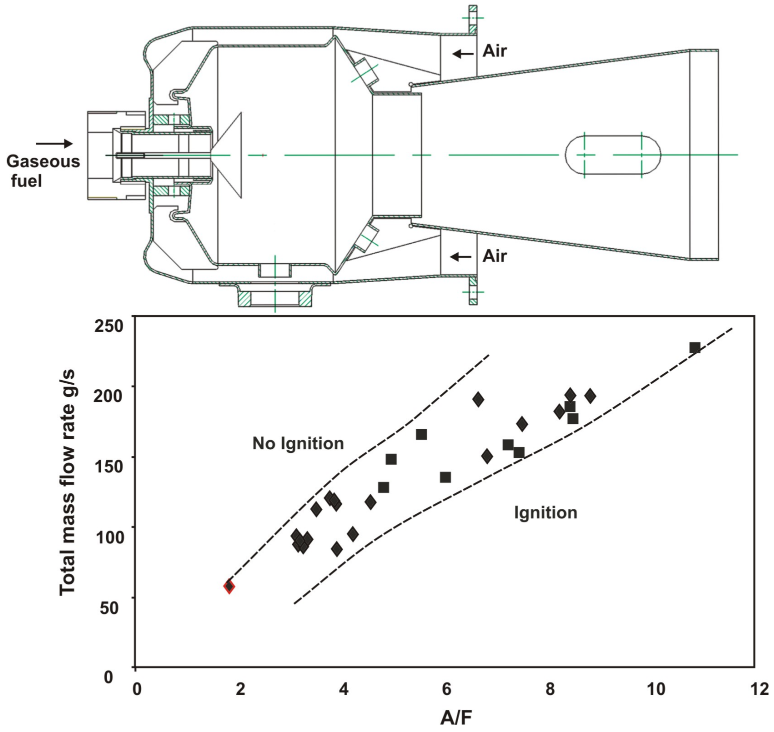

Figure 7.22: The reverse flow gas turbine combustor and the ignition/combustion regimes

biomass to the same level as for kerosene would need the use of a recuperator. This would allow smaller biomass consumption. But this would pose other problems - lesser gas flow rate into the combustion chamber but much larger air flow rate could make combustion unsustainable at these levels of dilution. Such a condition would need bypassing part of the compressed air for other possible uses. Taking such approaches would imply looking for new problems to find solutions; adopting existing gas turbines for operation on producer gas is quite difficult.

Biomass engineering company, UK (2004) conducted studies on gasifier-gas turbine under a contract. They used for these studies a 30 kWe capstone micro-turbine that normally works with natural gas and liquid fuels. The gasification system that was used was the classical closed top system with modifications to the design involving ceramic inner lining for the combustion zone, throat and reduction zone. The gasification system was a part of the development of such systems for power generation using reciprocating engines (a commercial operation they were engaged in) and was qualified for operation on gas turbine. The coupling to the gas turbine demanded a compressor and a recuperator as the demonstration was also intended to show efficiencies normally associated with these systems (26%). The presence of the recuperator also would demand a lower capacity of the gasifier. The development team faced operational issues because of hardwired control system elements on the micro-turbine that were inaccessible. Nevertheless, they showed that the gasifier - compressor - gas turbine would work well in the 500 hour run. The emissions were very low as expected of such systems. In terms of generation performance they could achieve was 11 kWe at 2 kg biomass/kWh. This would imply a biomass-to-electricity efficiency of 12 %. Without the recuperator the consumption rate would be about 4 - 5 kg/kWh (5 - 6 % efficiency).

They have also examined the techno-economics and shown that the system is far more expensive than gasifier-reciprocating engine option - nearly twice because this has to have a recuperator and a compressor in addition. The energy generation costs would be prohibitively large. The techno-economics of the option used by IISc is also expensive. The high pressure gasification system would cost twice as much as a ambient pressure system and the devoted gas turbine nearly twice as much as a reciprocating engine. Consequently, gasification - gas turbine route is not a competing proposition to gasifier - reciprocating engine route, technically or economically.

On the larger scale, the gasification system-gas turbine route has been examined at Varnamo, Sweden (Stahl et al, 2004). This project was initiated by the World bank with part funding to two industrial agencies - TPS and an agency which has been finally owned by Sydcraft. TPS used their atmospheric circulating fluid bed technology with a dolomite based tar cracking system to generate the gas. This gas would be compressed and delivered to a gas turbine.

Sydcraft used the Foster-wheeler high pressure gasification technology. A high pressure gasifier with suitable gas treatment to enable it for use in a gas turbine was the principal approach here. It was initially stated that only one design was allowed to be pursued depending on the state of readiness on a cut-off date. Finally, high pressure gasification route was chosen for final support (partial). The circulating fluid bed gasifier operating at a pressure of 18 atm has a cyclone that separates most reasonable size matter and returns it into the bottom part of the gasifier; the gas is taken from here through a heat exchanger where it is cooled to 300 to 400°C from where it is taken to a hot gas filter that was originally of ceramic design. Considerable experience on it showed problems and the system was changed to metal construction. The gas is then taken to the gas turbine combustion chamber operating at 15 - 16 atm. The power from the gas turbine is 4.2 MWe. The exit gas from the gas turbine goes to a steam power generator (40 atm, 455°C) to produce 1.8 MWe. The total electricity generated is 6 MWe and the heat of 9 MWth is put into district heating.

They have conducted experiments with a variety of biomass from wood, grass to refuse derived fuel and learnt how to feed the fuel on a continuous basis and operate the system for more than 8500 hours on gasifier mode including 3600 hours on an integrated IGCC mode (Integrated Gasification Combined Cycle). Despite these technical successes, the IGCC system has not been able to perform commercially successfully. It is a contrast that several waste systems based on gasification (like Techno-select) have performed commercially well even at large power levels (7.5 MWe). It appears that high pressure gasification route is technically elegant but financially unviable. Ambient pressure gasification and reciprocating engines seem far more viable.

7.11 Manufacture and commercial status

Producer gas as a part of charcoal gasifiers was known around World war II period in India particularly for transport applications. But this experience was lost sight of when fossil fuel availability became normal. Gas engine based operations have been conducted with societally meaningful results long ago by Imbert gasification company in Paraguay. Many essentials were learnt at that time, but lost or not completely understood because the scientific foundations were not created. This was largely because the effort was commercially based even from start. Catalyzing and sustaining the research activities in several institutions in India by the Ministry of New and Renewable Energy in the last thirty years has paid rich dividends. There were several manufacturers in the early period who helped to popularise the technology by building thermal systems for a number of applications. But building gasifiers for electrical applications requires a greater commitment that seems missing in many of the manufacturers. M/s Ankur Scientific company has stood the test of time and is into commercial operations of building closed top designs and improving upon a variety of aspects. The Tata Energy Research Institute (TERI) has made contributions to thermal systems and a number of studies on electrical applications. One of the issues in conducting research and development on producer gas is the non-availability of gasification systems that enables one to generate gas at a laboratory. Such gasification systems do not exist. The alternate pathway for conducting research would be to use a synthetic gas mixture. This will be far more expensive and it is unclear in the end if it serves any purpose beyond understanding. Combining application with understanding would lead to truly worthwhile results. It is this effort at IISc of building reliable small systems that allowed serious research to be conducted. Coupled with this was the development of system packages for several classes of applications has led to several licensed manufacturers of the technology in India and overseas; these manufacturers still depend on IISc for scientific support.

The cost of the gasification based power packages will be a driving force for commercial penetration. IPPs built in India about a decade back have equipment that costed around 1000 USD/kWe. These might cost around 1100 - 1400 USD/kWe currently with the gasification package and the power generation and evacuation equipment costing roughly equally. The rise in cost per kWe is partly due to rising expectations in terms of automation and control. The cost range covers small-to-large systems; smaller ones may not have as much of automation and some elements might be based on alternate approaches as well.

7.12 Fuel cells

Fuel cells are electro-chemical cells. They perform the function of a reverse of electrolysis where if one pumps electricity, one decomposes the fluid, say water into hydrogen and oxygen. If one pumps hydrogen and oxygen into a fuel cell that breaks these into ions, they combine to produce water, Since they need to move between electrodes, the movement of charge between the electrodes creates electric current. Unlike thermal engines, fuel cells can operate at a fixed temperature.

A comparison of various types of fuel cells, their features and efficiency are described in Table 7.10. The PEM type fuel cells are the only candidates of fuel cells for transport applications. The choice of the fuel for the first two types presented in Table 7.10 is hydrogen. The high temperature fuel cells can accept a combination of fuels including producer gas. When methane is used it is passed through a reformer to produce a $CO–H_2$ mixture to enable use in the fuel cells. It is only the DCFC that uses a solid fuel, namely carbon. There are also attempts to use coal directly. Most of the fuel cell development uses exotic materials, processes and manufacturing procedure and hence is heavily protected by intellectual property rights, some times by the industry working silently with no publication or open discussion. DCFC is one of the designs that has the possibility of not having to depend on the material technology as much as in others.

All the types of fuel cells have value in selected applications of defense or space. This is

Table 7.10: A comparison of the features and performance of various fuel cell types; PFMFC = Proton Exchange Membrane Fuel Cell; PAFC = Phosphoric Acid Fuel Cell; MCFC = Molten Carbonate Fuel Cell; SOFC = Solid Oxide Fuel Cell; DCFC = Direct carbon Fuel Cell

feature	PEMFC	PAFC	MCFC	SOFC	DCFC
Electrolyte	Polymer	Phosphoric acid	Molten Carbonate	Ceramics	KOH -carbonate
Cell Temp, °C	80	190	650	900 –1000	600 – 700
Fuel (s)	H_2	H_2	H_2/CO	H_2/CO/CH_4	Carbon
Reforming	Outside	Outside	Out/inside	Out/inside	not needed
Oxidant	Air/O_2	Air/O_2	Air/CO_2/O_2	Air/O_2	Humid air
Efficiency, %	30 - 35	45 - 55	50 - 55	45 - 55	70 - 80

particularly so because these are silent and have high power densities compared to other systems. When it comes to distributed power generation, there are two aspects. The first one is a question of efficiency. It is most often stated that the reason for choosing fuel cells is that they promise much higher efficiencies than internal combustion engines. It is true that when we consider large scale thermal power generation (hundreds of MWe), a limit of 36.5 % in tropical countries is not easy to overcome. These systems are built at costs of 800 – 1000 USD/kWe. Opportunities exist to build IGCC with coal at these power levels with a promise of 43 to 45 % efficiency. These might cost 1800 USD/kWe. Low rpm reciprocating engines produce electricity at efficiencies of 50% + even with fuels more crude than diesel. Excepting for alkaline fuel cells that are claimed to have efficiencies of 60 % with more significant military and space applications, other efficiencies are between 30 - 55 % (other than DCFC). Further, current costs of fuels cells are around 3000 USD/kWe at 1 MWe class of power level. In most of these discussions inadequate attention is paid to the question of fuel. If it is natural gas, as it is so with current thinking, its efficiency will possibly be slightly more than high efficiency reciprocating engines and tenuous arguments on economic grounds need to made to promote fuel cells. Biogas is a good possibility as it is a distributed source of fuel not highly valued, certainly not as much as natural gas. In this case, the magnitude of outreach will be limited. If it is hydrogen, one needs to conceive of economically meaningful generation of hydrogen, perhaps from renewable sources. These will happen in the next decade. However, questions of storage and transportation of hydrogen are being raised again and again without convincing answers yet. The possibility of using producer gas in fuel cells (like SOFC and MCFC) is realistic technically, but it is difficult to conceive of economically meaningful possibilities except in niche applications. Hence fuel cells will take a long time to compete with the traditional sources. One fuel cell category that is close to biomass or coal that is not discussed at the same level of possibility in most literature on fuel cells is the Direct Carbon Fuel Cell (DCFC). In a workshop held in the USA in 2005 (see NETL, 2010 for the papers presented at this workshop), many aspects of DCFC have been discussed. This system is claimed to have efficiencies close to 80 % in theory and 65 – 68 % in reality. Only laboratory size systems have been built and results obtained. The performance of this system is so much superior to traditional systems, that much effort needs to be put in for further development. More discussion on this appears in Chapter 12 (see section 12.4).

7.13 Summary

This chapter has been concerned with high grade heat or electric power from producer gas. Several routes for energy have been discussed. One of the key aspects in the design of energy packages is that the users prefer to have a back-up fuel or energy source to meet with possible system failures or more importantly non-availability of a specific fuel.

High grade heat from piped gas into a specific location in an industry is a direct possibility most usually in a dual-fuel mode with either mode being used without having to mix them allows the user to combine economic operation with availability.

Diesel power is very expensive; fuel oil (furnace oil) power at 2 - 3 MWe occurs at high efficiency $\sim$ 40 %. Yet, it has also become expensive. Some designs promise efficiencies around 50 %. There is a demand from pollution control authorities to reduce emissions from these systems. This will need the use of natural gas if it is available in the vicinity or biomass based system – producer gas based power. However, even with 80 % fossil fuel replacement, the cost of power even in this case is not small. It is only the producer gas based engine that promises the economy of power generation.

Small power with gas engine is obtained at 1 - 1.2 kg biomass per kWh with sun-dry biomass having an ash content less than 1.5 %, At large power levels, one should expect to get the power at 0.8 – 0.9 kg/kWh. Consistent demonstration of this has yet to take place. This is related to use of high BMEP engines as well as best practices in power plant operation including the use of biomass fuel of minimum moisture and right size distribution. Multi-generation possibilities enhance the economics of operation. Even though wood itself offers this possibility, agricultural residue like coconut shell offers more attractive possibilities.

Gaseous emissions from reciprocating engine operations show that NO_x is reduced with producer gas but CO will be beyond acceptable limits. Reduction of CO calls for the use of catalytic converter for the exhaust gas.

Gas turbine based power appears interesting at first sight. Tests show that technical possibilities are achieved at small and large power levels. Economics of power plant installation and operation does not favor it unless the scale of the operation is large. Even at large power levels it has to compete with reciprocating engine route. Installing large power plants in India would call for a careful assessment of commercially and environmentally meaningful sustained biomass supply chain.

Fuel cells have been emphasized for the possibility of enhanced efficiencies and it is suggested that economics related to first cost is the only impediment. Its support in advanced countries for stationary power generation will take time to create commercial availability except in niche applications.

Small power generation from external combustion like Stirling engine is some times thought of in conjunction with gasification systems as it is thought that arranging combustion source as required for the engine is simpler. This is certainly a possibility. However, simpler combustion systems using reverse downdraft systems will be addressed in a later chapter.

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8 Gasifier stoves

Research, development and dissemination on biomass based domestic combustion devices otherwise termed cook stoves has a long history of over 5 decades. Many of the developments have occurred due to intuitive approaches to examine heat transfer aspects relegating the combustion issues to a peripheral state. A broad summary of the scientific work performed till mid-eighties is reflected in the work of Prasad et al (1985). Over a hundred designs from all parts of the world have been documented and these are discussed in a website devoted to cook stoves (www.bioenergylists.org). Stoves are made of metal, mud, refractories of various qualities with and without chimney. Chimney based stoves are considered superior to chimney-less stoves because any emission is taken out of the kitchen thus preserving the indoor air quality. However, these emissions create a load on the environment something that has become a matter of serious concern in the last several years. Further, even the single pan stoves without chimney have air supply by free convection since electric supply was not to be found in most rural dwellings which is where these stoves were largely expected to be used. Most of the these stoves had utilization efficiencies assessed by water boiling tests between 10 to 20% (see for instance, Bhattacharya et al, 2002a, 2002b) while one slightly complex design shows an efficiency of 40% at small power levels (see Mukunda et al, 1988 for details). It has been known that both kerosene and LPG (liquified petroleum gas) stoves have efficiencies as high as 65 and 70 %. The scientific question as to what limits the efficiencies in biomass stoves in comparison to kerosene and LPG stoves had remained unexamined till Mukunda et al[4] studied this aspect experimentally. They specifically showed that *the efficiency is directly related to the operation of the stove at near-stoichiometric conditions that lead to peak combustion temperature of the product gases*; it is this temperature that influences the heat transferred to the vessel within the limited bottom area available. Hence, the stove operation can be expected to be the best when the air-to-fuel ratio is maintained near stoichiometry, albeit on the lean side to ensure minimum CO emissions; limiting the emissions of NO_x is taken care of naturally by the lower combustion temperatures of biomass-air system as thermal NO_x is the predominant source. Limiting the velocities in the fuel residing zone will help limit the particulate carry over.

The stove designs that have (a) free convection based air ingestion and (b) biomass loaded as and when it is thought fit into the hot combustion zone will function with air-to-fuel ratios that can be very rich or very lean. The former condition leads to sooting and the latter to smoking. Also parts of the fuel over the stove may still be cold leading to air flow out of the stove body without participating in the combustion while other areas are deprived of the needed air for combustion. Coupled to all these, the biomass may either be dry or very wet. The latter condition will lead to poor combustion with heavy smoking. Thus improvement of biomass based stove combustion involves biomass quality as well as combustion aerodynamics, a view point that has not been adequately reflected either in the stove literature or in the development of improved cook stove initiatives in the past. The principal way of improving the combustion quality would be to supply air at the right air-to-fuel ratio. This is done by a fan. These are the fan-based stoves with the air supply capable of being used in several ways, some of which are discussed below.

Typical specifications of a domestic stove can be derived from comparable stoves based on kerosene or LPG that have a input power level of about 2.0 kWth (~ 3 g/min of LPG). Accounting for efficiency differences, the biomass stove input power level can be set at about 3 kWth (12 g/min of biomass). The stove must allow continuous operation and if not, must last the complete cooking duration that has been estimated as about one hour. One would expect to have clean combustion with minimal emissions. Minimizing emissions of CO and other unburnt products of combustion calls for maximizing the combustion efficiency and minimizing CO_2 emissions implies maximizing the utilization efficiency (or water boiling efficiency on vessels of practical relevance). One would desire a smooth start-up and some control on the power level. The life of the stove must be large, at least for two to three years. In doing all these, the cost of the stove must be affordable.

In dealing with semi-industrial applications like in hospitality industry or community cooking, one needs a larger power stove (100 g/min or 25 kWth) and longer burn durations. There are applications that demand short fixed burn durations as well long durations. These demand facilitating continuous operation.

There are two classes of gasifier stoves discussed in this chapter. The first one is meant for pellets and briquettes and has a fixed burn duration. The second one is meant for a variety of prepared fuels that include sized firewood, pellets, briquettes or other agro-residues to burn in a continuous mode. It is based on ejector induced gasification with a horizontal feed for the fuel. It is called EIGAS stove. The difference between the two is that the electrical energy required to operate a small stove is less for pellet gasifier stove compared to EIGAS stove and the quality of combustion in pellet gasifier stove is excellent all through the burn. The EIGAS stove has equally good quality flame at all high power levels. At low power levels (~ 3 kWth), good quality combustion is obtained most of the time. The fuel feed and adjustment actions (absent in the pellet stove where it is fire and forget feature) create occasional decreased quality of combustion and emission of particulate matter where the choice of the fan is such that the energy put into the ejector action is to be kept at a minimum. We will examine both these classes of stoves.

8.1 Principles of pellet gasifier stove

Research relevant to pellet stoves can be traced to rice hull gasification systems that used a vertical cylinder filled with rice hull and air drawn through the packed bed from the top. While these were first developed in China as early as in 1967, the scientific investigation was conducted by Kaupp (1981). In this reactor, shown on the left side of Figure 8.1, one can use biomass like wood chips, and pellets apart from rice hulls for which it was first conceived. If now the reactor is inverted, implying – operated such that air flows from the bottom and the fuel surface at the top is lit, one would get combustible gases that will burn above the top surface with ambient air or with additional air supplied towards the top. Such a configuration, shown on the right side of Figure 8.1 termed *reverse downdraft gasifier* constitutes the essence of a pellet gasifier stove. It was this stove design that was used to determine the superficial velocities that cause ash fusion in agricultural residues (see chapter 6, Fig. 6.25) An important consequence of this mode of operation is that the combustible gas exiting from the top of the packed bed bears a fixed ratio to the amount of air introduced for gasification (primary air flowing from the bottom). The reduction reactions following the oxidation, limit the amount of fuel to be consumed due to the endothermic nature of these reactions. The interesting feature is that the *relative amounts* of fuel consumed and air introduced remain the same and increased amount of solid is consumed when primary air flow rate increases (see Chapter 6, section 6.6).

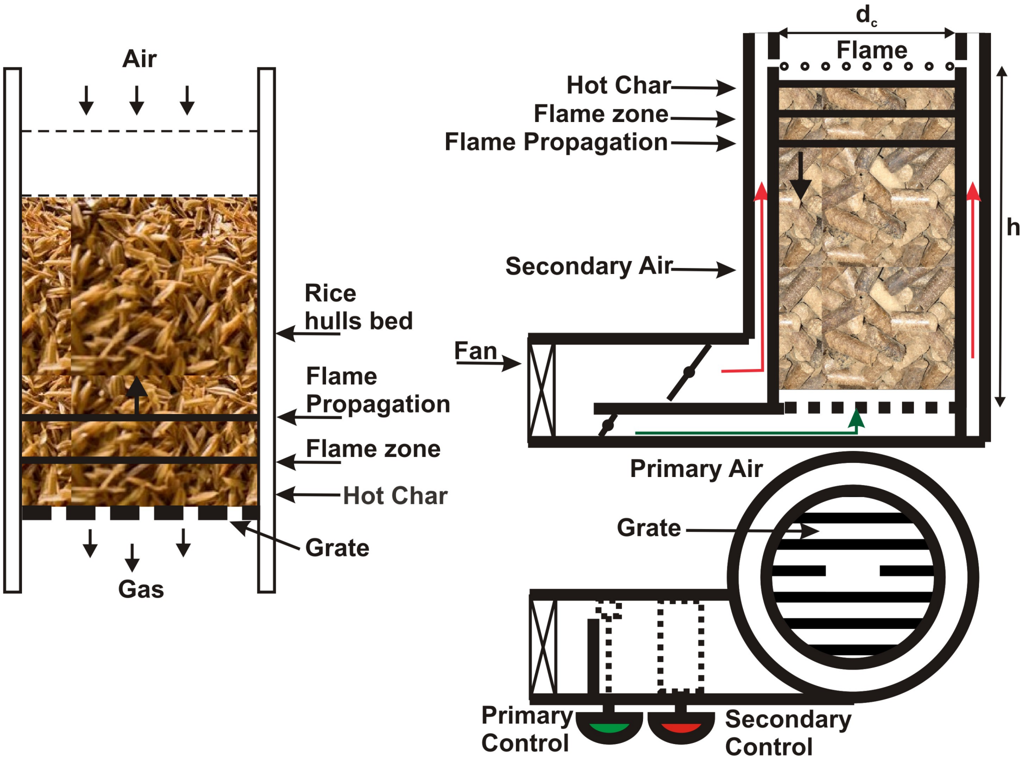

Figure 8.1: The left side of the figure is schematic view of a rice hull gasifier. Note that the air flows from the open top towards the bottom. The right side is a schematic of a reverse downdraft gasifier stove where the gasification air flows from bottom to top

Thus the power of the stove is proportional to the primary air flow rate. The gases coming out of the bed will be at a temperature of 800 to 1100 K and will be composed of CO, H_2, CH_4, H_2O (as gas), some higher hydrocarbons and N_2. These gases are burnt to CO_2 and H_2O with a second stream of air which is introduced in the top region for this purpose. Based on the early work of La- Fontaine and Reed (1993), Reed and colleagues developed a free convection based *gasifier stove* [Reed and Larson (1996)] and have subsequently discussed the development of forced convection based *gasifier stove* (Reed et al, 1999, 2000). The biomass is largely wood chips and the forced convection depended on a fan; it formed the basis of camp stove and this is indeed how it got marketed. One of the key aspects that helped the development of these stoves at the IISc was the availability of mass produced computer fans that reduced the cost of storage battery based fans, for otherwise, the development would have got limited to fulfilling a research curiosity. These low power fans at 1 - 2 W could be obtained or built at less than 5 USD per system including the electrics. The work on gasification as well as free convective stoves was going on from 1982 at IISc (see chapter 6 and Mukunda, 1988) was spooled into the development of stoves of high efficiency and low emissions.

8.2 Free vs. Forced convection stoves

Nearly all the domestic cook stoves over the world are free convection driven. In several of these designs the free convective driving potential is so small that the smallest of ambient disturbances can affect the air flow through the stove. Even in better of these designs with a column of hot zone (due to the combustion chamber) that enables stabilize the flow through the stove, flow disturbances caused by varying heat release across the section of the combustion chamber due to randomly located and moved-around pieces of "firewood" leads to widely varying air-to-fuel ratios locally. This kind of a variation reduces the peak flame temperature most of the time and leads to emissions of CO, unburnt hydrocarbons (UHC) and particulates significantly. Even when better efficiencies are obtained, the stove operation becomes very rich and significant sooting will result. This is particularly because, faster cooking is understood to be obtained at a larger fuel burn rate and this is achieved by introducing more fuel into the combustion space. Getting good emission performance from such stoves is usually a difficult task.

Free convective stoves were and even now, are considered inevitable because of the perception that such stoves provide the "choice" and flexibility and allow the users to continue to use whatever non-processed raw biomass and/or wood they were using. Also, the use of any forced draft that requires electricity is seen as difficult for electricity itself is unavailable. Technical solutions were to be found to overcome the distinctly poorer performance on efficiencies and emissions that have been observed on free convection stoves. This does not imply that the rural environment enjoys the availability of electricity all the time; perhaps, they have it over a few hours a day. Yet, the fact that electricity is available over some period can be made use of for the use of electricity enabled stove designs. Also, it is possible that nothing better than free convection stove can be contemplated in regions deprived of electricity totally. This should not mean that other regions that have electricity support even over the part of day should be deprived of modern technology interventions.

In comparison to the above mentioned designs, gasifier stoves with loaded fuel provide one alternative. Gasifier stove that has loaded fuel pellets/pieces can be conceived from the end user as a starting point. Starting with the amount of cooking energy needed to cook one meal, the design of the stove was arrived at in combination with amount of fuel to be loaded in such a way that the operation is relatively foolproof. The stove operation is dependent on thermo-chemistry which modulates the gas production process. At any fixed power level, the gas composition and temperature remain steady and with appropriate secondary air flow, the flame will get maintained at its peak temperature in a near-steady mode. However, when power variation is demanded, it takes a transition time (of about a few minutes) much unlike a gas stove since the thermal inertia in the hot fuel bed has to be overcome in the process of reaching a new steady state. This design while providing flame control to the users, also makes it less user-dependent for achieving desired efficiency and emissions and it may be expected that field results would be close to those obtained at the laboratory.

8.3 Fuel for the stoves

Historically, biomass stoves imply "firewood" stoves. It is generally thought that firewood of any size, shape should be acceptable; moisture in the firewood is known to be undesirable, but there is no rigor in ensuring dry biomass use in stoves. The national statistics on fuel use in cook stoves in rural and urban environments is presented in Table 8.1. This table is composed from the data provided in Ravindranath and Hall (1995), Shukla (1997), Kishore et al (2004) and TERI (2004/05). There are differences between various studies and the data of Table 8.1 can be expected to have inaccuracies up to 15%.

The data in the Table 8.1 is very revealing. While wood and agro-residues are both biomass, the amount of agro-residues used on a per house-hold basis is nearly twice that of wood. While it is generally understood that wood use itself is inefficient, the degree of wastefulness of agro-

Table 8.1: National fuel usage in rural and urban households and energy efficiency, hh = hosehold, mhh = million household, mmt = million metric tonnes, yr = year, t = tonnes, GJ = Gega Joules

Fuel type	Rural mhh	Urban mhh	Fuel used mmt/yr	Unit fuel t/yr/hh	Unit energy GJ/yr/hh
Firewood	87	15	250	2.5	40.0
Agro-residue	20	2	120	5.5	77.0
Cowdung cake	20	2	95	4.3	55.0
Coal, coke	2	2	6	1.5	27.0
Kerosene	2	8	5	0.5	21.0
LPG	9	25	8	0.24	5.7
Others	1	2	-	-	
Total	141	66	465[a]	3.2[a,b]	47[a,b]

[a] includes solid bio-fuels only, [b] national averages

residues is enormous, a fact about which *there is still not adequate appreciation all-round*. If developing improving cook stoves on firewood is considered important, it is *far more important* to develop stoves to burn agro-residues that are light and odd shaped to obtain high efficiency and reduce the emissions. The magnitude of the use of bovine dung cake as a source for fuel is non-insignificant, but its use is about as energy-inefficient as agro-residues. However, the emissions from its use are significant and any improvement in the use of bovine dung cake should address this aspect as well. Coal is used in a wasteful way largely because of ignition problem. Many of the stoves are lit in the open for the volatiles to escape (coal has about 30 % in comparison to biomass with 70 % volatiles) until coal becomes virtually coke and its combustion becomes vigorous. China that has encouraged a large production of coal-powder based beehive briquettes has serious indoor air pollution problems related to this fact (Sinton and Smith, 1995).

LPG and kerosene are more sought-after fuels and are in the upper region of the energy ladder. Hence, they turn out to be important as reference for performance comparison. Kerosene is a fuel used to a larger extent by the urban poor with relatively small kitchens and cannot afford the costs of LPG for cooking. Both these have higher water boiling efficiency. Laboratory experiments have shown water boiling efficiencies of 70 to 75 % for LPG stoves and 60 to 65 % for kerosene stoves. Kerosene use as fuel on a per-household basis appears large while the usage of LPG seems not unreasonable (one 14 kg cylinder for three weeks for a family of five). The (lower) calorific values of biomass, kerosene and LPG are 16, 42, and 45 MJ/kg and on this basis, one would have expected kerosene usage to be about 30 % higher than LPG allowing for differences in the utilization efficiency. Perhaps, the magnitude reported on kerosene use for cooking may be inaccurate as it is generally known that significant amount of kerosene bought under public distribution scheme at subsidized prices is sold away as either cooking fuel or fuel for adulteration with gasoline at higher prices.

The calorific value ratio coupled with efficiency differences allows speculation on how much of solid biomass is needed for domestic cooking on a national scale. The equivalent of 0.24 tonnes/yr/hh of LPG translates to about 1.20 t/yr/hh [$0.24 \times (45/16) \times (70/40)$]. Achieving this implies that one would aim at a total solid biofuel use for cooking of 253 mmt/year as against the current estimate of 465 mmt/year. The magnitude of the task can be understood if we note the current efficiencies of firewood stoves as 20 %, of agro-residue based stoves (or their use in the same firewood stoves) at 10 % and bovine dung cakes as 12 %. Enhancing the efficiency of the use of agro-residue based fuels and bovine dung cakes must occupy the highest attention, next to which is firewood. Bovine dung can perhaps be integrated into the strategy for better fuel making without any special stove design for bovine dung cakes; fuels based on agro-residues and bovine dung should be dealt with as a separate development task.

8.3.1 Issues with agro-residues and bovine dung

The availability and characteristics of agro-residues have been discussed in many earlier chapters (chapter 1, 2 and 6). Briefly restated, it has been brought out that the density of most residues is very small and for the purposes of economic transportation, one should pelletize or briquette them. Approaching high efficiencies of a LPG stove demands that the combustion volume be brought down to as low a value as possible and is aided by densification. This will have benefits of lower inert material content and associated reduction in heat loss.

Binderless briquetting achieves a density of 1000 to 1100 kg/m^3 and will be suitable for large stoves and combustion devices. This would form an upper limit to which the material must be densified. Since the requirement in stoves will turn out to be small sized pieces, one needs to produce pellets, typically of 10 to 12 mm diameter and up to 40 mm long to obtain good packing density. This is done by the process of pelleting. Pellet making and briquetting have very different process fundamentals. Briquetting process uses very high pressures, of the order of 1200 atms to generate heat due to friction between the material and the die wall to raise the temperature up to 350 °C to enable lignin to be released. This lignin acts as a powerful binder. Pelleting process uses moisture or steam in extruding the material through a small die; the temperatures achieved are not high, typically, around 100 to 120 °C. Under these conditions, the crude protein present in the biomass is softened and helps in the binding process. The densities achieved are usually lower than in binderless briquetting and are typically about 500 to 800 kg/m^3. The presence of crude protein is important and hence any kind of ingredients having some amount would aid in the process and enhancing the throughput of the system.

Bovine dung is a major cooking fuel in north India, perhaps in conjunction with agro-residues or firewood. Huge mounds of dry bovine dung are set around houses to enable peal-off and use in the stoves. Bovine dung itself has components that could help pelleting in both the intrinsic feed material (to the bovines) and due to what happens in the rumen of the bovines. This is an important task for the future.

Typical agro-fuels used currently are bagasse and groundnut shell as primary fuels along with tamarind husk, de-oiled ricebran, sawdust, and other seasonally available wastes as secondary ingredients. Considerable experience has been accumulated on fodder pellet making machines (by a commercial group that has the license to produce these stoves and supply pellets. see Mukunda et al, 2010). The fuel pellet throughput comes down to 50 to 60 % of the fodder pellet throughput with increased maintenance.

8.4 The stove, efficiency and emissions

An important aspect that was uncovered during the study (Mukunda et al, 2010) that obtaining the highest combustion efficiency (and accompanying utilization efficiency) with relatively short visible flame heights would lead to high efficiencies and reduce the emissions. The amount of secondary air was varied to obtain a short visible flame. This meant that the ambient air demanded for combustion was minimal. Figure 8.2 shows the plot of the mass of the fuel burnt with time. As can be noticed, there are two distinct phases of heat release. The first part is due to flaming and the second part due to char combustion. The curves for wood chips, coconut shell and rice husk pellets are different because the amount of the material loaded will be different

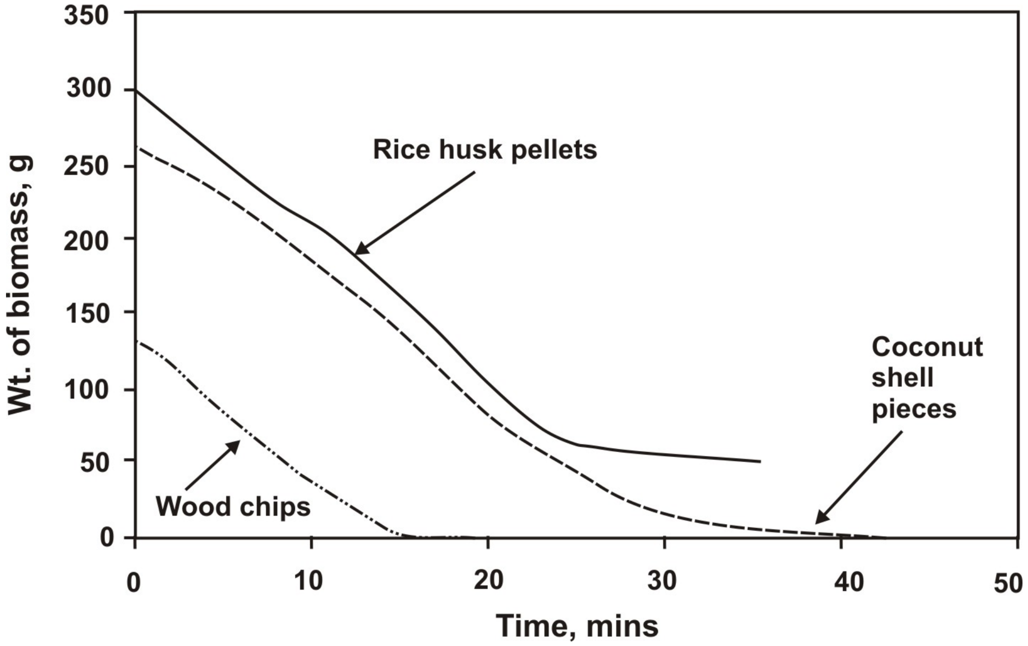

Figure 8.2: The mass of the fuel with time during the stove efficiency tests. The slope of the curve gives the mass loss rate

Table 8.2: Water boiling experiments - stove geometry, fuels and performance, WC = Wood chips, RHB = rice husk briquette pieces, CS = coconut shell pieces, MP = Marigold waste pellets, $^+$ The split-up is between flaming and char combustion times, * Power over the flaming time

biomass	ρ_{bulk} kg/m^3	moisture %	ash %	biomass loaded, g	burn time$^+$ mins	Power* kWth	η_{wb} %
Stove dia. = 100 mm, chamber volume = 0.6 liter, Vessel = 10 liter							
WC	220	10	0.8	130	14 + 5	2.3	49.3
RHB + WC	500	7	18.3	250 + 50	27 + 10	1.9	49.3
CS + WC	430	9	0.6	230 + 30	30 + 10	2.2	53.3
MP + WC	366	12	11.3	225 + 30	18 + 7	2.5	49.1

because of the intrinsic density of the pieces. The curves settle down to negligible mass in the case of wood and coconut shells because of the very low ash content. Rice husk pellets have an ash content of 20% and hence the final mass is much higher. The power output during the second phase of char combustion is about one-fourth of the power in the first phase. The slope of the mass vs. time plot gives the mass loss rate that is the same as burn rate; this quantity multiplied by the calorific value will give the power of the stove. The second part will have a lower power because the heat release rate of the char is much less than with volatiles in the biomass at the same air flow rate. If the power has to be brought up, then the air flow rate has to be increased in the char burning mode. The performance of the stove is presented in Table 8.2. one can notice that high efficiencies ($\sim$ 50%) can be obtained from such stoves with pellets made of a variety of agro-residues. In the table it can be seen that a certain amount of wood chips (WC) is loaded. This is loaded at the top to reduce the time for getting the stove into steady mode. The lower density wood chips are lit with a sprinkle of alcohol or kerosene and they will burn till the higher density pellets catch up.

In stove literature, the nature of vessel is given very little or very subsidiary importance. The amount of heat extracted from the combustion products can be enhanced through a suitable choice of the vessel diameter for the same volume. The results on vessel diameter effect with the

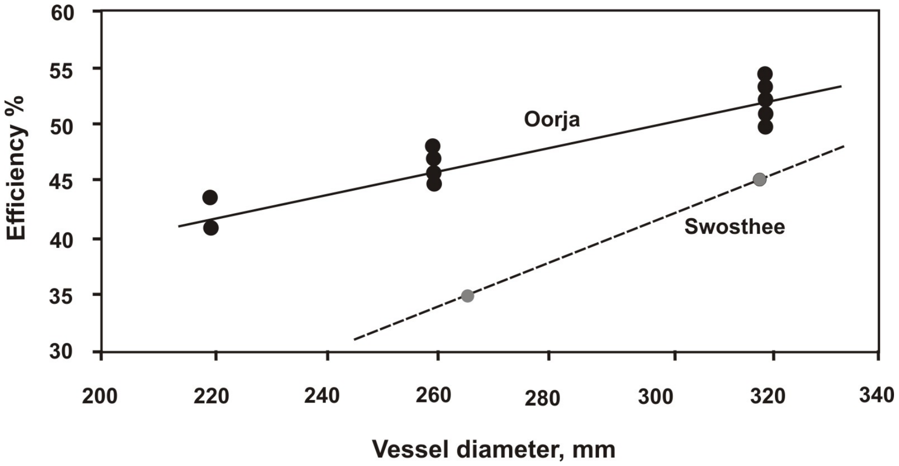

Figure 8.3: The effect of vessel diameter on efficiency, the lower plot is for the stove named Swosthee (Mukunda, et al, 1988)

100 mm dia stove are also shown in Figure 8.3. It is clear that there is significant enhancement in the efficiency with vessel diameter. This implies that given an option of a cooking vessel with a desired volume, it would be better to select a vessel with as low a height-to-diameter value as is practical. This result was also found in the earlier study of Mukunda et al[4] albiet with lower efficiencies with a stove named "Swosthee" (for Single pan WOod SToves of High EfficiEncy) that is similar in configuration and performance to the currently prevalent rocket stove. Scaling the design of this stove for other power levels is straightforward. We first recognize that at the design superficial velocity of 0.05 m/s, the power level (P) of the stove is 3 kWth for a inner diameter of 100 mm. The power level scales as the area of the combustion chamber (A_c). Thus $P = 3(A_c/78)^2$ kWth. One can use a circular or square combustion chamber. If the burn time has to be increased at a fixed power level, the combustion chamber depth is to be increased linearly.

The air for combustion of the gases is provided above the top of the bed. The amount of air (secondary air) that has to be provided here is the difference between the stoichiometric combustion air for the biomass and the air supplied for gasification. For biomass, the stoichiometric combustion air depends on the CHNO analysis of the fuel. For the range of fuels considered here, the stoichiometric air-to-fuel ratio is about 6.0 (the fuel is allowed 10 % ash with corresponding reduction in the air-to-fuel ratio). For the current design, for 12 g/min of burn rate, the primary air is 18 g/min and the secondary air will therefore be 54 g/min. This is supplied through a large number of holes of small diameter. In the current design, 18 holes of 6.5 mm dia (an area of 597 mm^2) are provided. This leads to an inward air velocity of 1.8 m/s through the holes. This criticality of this air flow is more towards determining the emission rather than efficiency. For, if this air flow is inadequate, some part of the air from the ambient atmosphere is drawn in for combustion; but the oxidation of carbon monoxide in the product stream is affected, for it is very slow to combust. Hence, the provision of a slightly larger secondary air flow will not affect the performance. Also, the fuel pellets made from a wide variety of agro-residues cannot be expected to have the same CHNO composition. As such, some variations in the stoichiometric air requirement can be expected; thus, if by design a slight excess air is introduced, it would account for these variations in limiting the CO emissions. Before release of the stove for developments involving engineering and production, emission measurements carried out at fuel consumption rates of 12 and 9 g/min showed that the CO emissions were 1 and 1.3 g/MJ where as particulate emissions were 10 and 6 mg/MJ for the two power levels.

Figure 8.4: The pellet stove (a) notice the power pack towards the left bottom section of the left plate (b) the ceramic combustion chamber with grate at the bottom and secondary air holes towards the top

The first phase - flaming mode shows a very low CO/CO_2 (< 0.01). The transition to char mode of operation increases the emission of CO significantly. The fact that char combustion in stoves has significant CO emissions is well known in stove literature [see for recent data, Smith et al (2000), Still (2006)]. The overall CO/CO_2 was found as 0.01 (volumetric) even though char burn alone creates far more CO. In fact free-convective stoves with charcoal are a part of Indo-china domestic cooking. There is no way of reducing the emissions unless fan based combustion system is introduced. In fact, the pellet stove will also work for charcoal if the primary air flow is increased to a level where the superficial velocities will be more than about 7 cm/s. What more, the efficiencies classically reported for these stoves will improve substantially - from about 25% to a value between 50 and 60% depending on the superficial velocity adopted.

8.4.1 The stove

Figure 8.4 shows the photograph of the stove in two orientations. The inner wall is made of ceramic composition that removes the limitations of the material limited life issues in the combustion chamber. The bottom grate is made of cast iron that ensures long life. The primary air comes through the grate and the secondary air issues out of holes seen at the top. The combustion process inside the stove is seen in Figure 8.5. The cup-like flames are those formed around the air jets issuing from the wall. Except for the initial lighting process during which the flames are yet to acquire the character of the combustion of a gasified fuel, all subsequent flame behavior is similar to what is seen in Figure 8.5. The results of the study on the variations in the area of secondary air introduction are shown in the Figure 8.6. As can be noted, the amount of CO_2/unit fuel and NO in mg/MJ basis are roughly constant and SO_2 seems insignificant as expected for biomass. The efficiency also does not change in the range shown. However, *CO decreases with increase in the secondary hole area significantly*.

8.5 EIGAS stoves

This design uses a horizontal leg for feeding the biomass in the form of firewood largely, could be other agro-residues including pellets. This enables accessibility of the fuel feed port for introducing fuel when needed. The crucial element of the stove is the ejector through which air

Figure 8.5: The combustion process in the Oorja stove

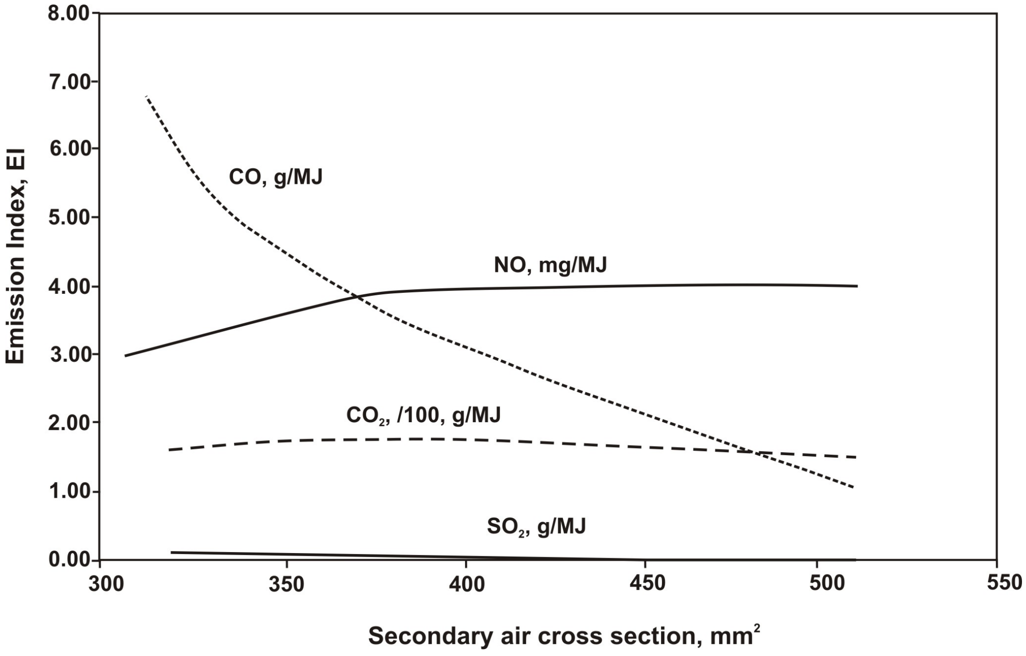

Figure 8.6: CO, NO and SO_2 Emission indices with secondary air hole area

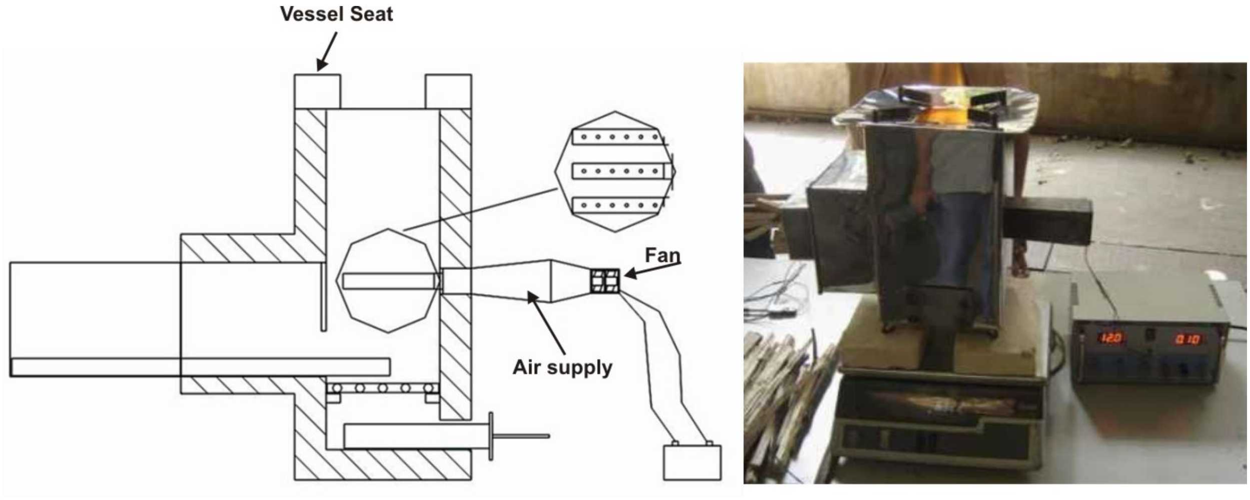

Figure 8.7: The sketch of the stove and a laboratory working system of 1 kg/h

is introduced in the form of fine high velocity jets, at velocities of 10 to 25 m/s, the jets emerging from a zone above the fuel feeding section. This creates a low pressure in the fuel feeding area. This causes suction in the fuel feeding port and therefore draws air through it. When the front end of the fuel pieces gets lit, a flame front or really a pyrolysis front will propagate through the solid fuel bed much like in a classical open top system. This process generates combustible volatiles that burn in the vertical combustion chamber after mixing with the high speed jets of air. The grate allows the hot charcoal to drop into the bottom section. When the operation has gone along to allow the bottom area to be filled with hot charcoal, the ash tray can be opened slightly to allow air to be drawn through the bottom section. This permits the oxidation of char and it contributes to the heat delivered by the stove. If this conversion process is partial due to the char bed being thick, then the products have an opportunity to be further oxidized with the primary air jets. Apart from the ejector action, the second most crucial element of the stove design is the throat plate at the combustion end of the fuel feeding port. This acts much like a throat in a classical downdraft gasifier. All the gases need to pass through a smaller section than the fuel port area. The bottom of the fuel feeding port including the zone over the grate is filled with charcoal. The gases passing through the charcoal bed allow the thermal cracking of the larger fragment of volatiles of the kind ascribed to the throat region in a classical downdraft gasifier. This makes the gaseous fuel fragments far easier to burn without sooting. Under normal operation, the throat plate becomes red hot.This radiated heat into the fuel port enables the pyrolysis to proceed and in the presence of air being drawn through the port, there will be "flaming pyrolysis" inside the fuel port close to the throat plate. This makes stove operation not depend on fuel tending often. In order to truly benefit from the ideas of gasification, the fuel port is to be run full with fuel except at the starting period. This will also help operate the stove without having to not tend for up to 15 to 20 mins. In order to start-up the stove the bottom ash port is kept closed to ensure better suction through the fuel feeding port.

The air flow from the jets is maintained such that it is stoichiometrically appropriate for the fuel burn rate (the ratio being about 6). If this air flow rate is obtained with finer jets at higher velocity, the suction is higher and the performance better. But this will call for more energy to be put into the fan and of course a batter fan implying one that operates at higher speeds and with better efficiency. These are not as important for pellet gasifier stove because what one needs to deal with is the pressure drop through the bed. In the case of ejector based

Table 8.3: Efficiency and emissions of various classes of stoves

Nature of stoves	WBE %	CO g/MJ	PM mg/MJ
Free convective based designs mud, ceramic, metal	15 - 35	1.5 - 15	30 to 1000
Fan based stoves	35 - 45	0.8 - 1.2	2 to 20
Optimized gasifier fan stove	40 to 50	0.8 - 1.0	2 to 9

gasifier stove, the ejector action which is essentially a viscous action of the jet that causes the low pressure and induces the flow. This effect is indirect. This is the reason why one needs a higher-pressure-building fan to cause higher velocities. Experimentally, it has been found that well designed fans operating above 2500 rpm would be adequate. Also the downstream flow profile should be handled delicately to reduce the losses and ensure all the momentum is transferred to the jets.

Stoves of this design have been built at 1, 3, 5, 10 kg/h. For the larger stoves that need higher flow rates, a double stage fan with levitating bearings (of the kind Sunon make, South Korea) would meet the requirements adequately. The specific advantage of such fans is the power needed to operate is low and can be dealt with by battery based energy supply. For the 1 kg/h stove, the power needed is 1.2 W at 12 V. The fan-battery electrics could be altered by suitable redesign if lower voltage is demanded.

Water boiling efficiency and emission measurements have been made on the stove. The results show efficiencies of 45% for the 1 kg/h stove and 50 to 53% for 3 and 10 kg/h stoves. Of course, in these cases, the power delivered is so large that larger vessels were to be used to extract the heat meaningfully. The emissions in the stoves have stood at 1 - 1.5 g CO/MJ and 5 to 15 mg particulate matter (PM)/MJ. The particulate matter emission is a function of the combustion chamber size. It is possible to operate any one of these stoves at a higher power level simply by raising the air flow rate through the air jets, typically by a factor of 1.5. But then the particulate emissions become significant. Thus the upper limit of the power from any one of these stoves is set by the emission of particulate matter.

8.6 Efficiency vs emissions

There is a body of a number of studies on stoves in respect of efficiencies and emissions. Most early studies are on free convection based stoves made of metal, mud, and ceramics with single, two and three pots. Smith et al (1994, 2000) have conducted an exhaustive and careful study of the emissions of a variety of stoves in India. There are a number of studies by Kirk Smith and colleagues on the greenhouse gas emissions from domestic stoves in several countries (see the publication list of Prof. Kirk Smith). Bhattacharya et al (2002a, 2002b) have presented the results of similar stoves from south east Asia and India. Still (2006) has compiled the measurements of efficiency of and emissions from about 20 stoves, only six of which are relevant here (several stoves are with chimney). These stoves contain the data of fan based stoves as well. A class of stoves termed TLUD (implying top lit up-draft) around the development of Reed and co-workers (1996, 1999, 2000) has been popularized by Anderson [see Anderson et al (2007)]. The results are set out in a summary form in Table 8.3 and in Figure 8.8 with data from the above sources. The wide range of efficiencies and emissions in free convective based designs is not unexpected since there is no possibility of controlling the emissions due to free-convective mode of operation. The key problem of free-convection based stove is that while

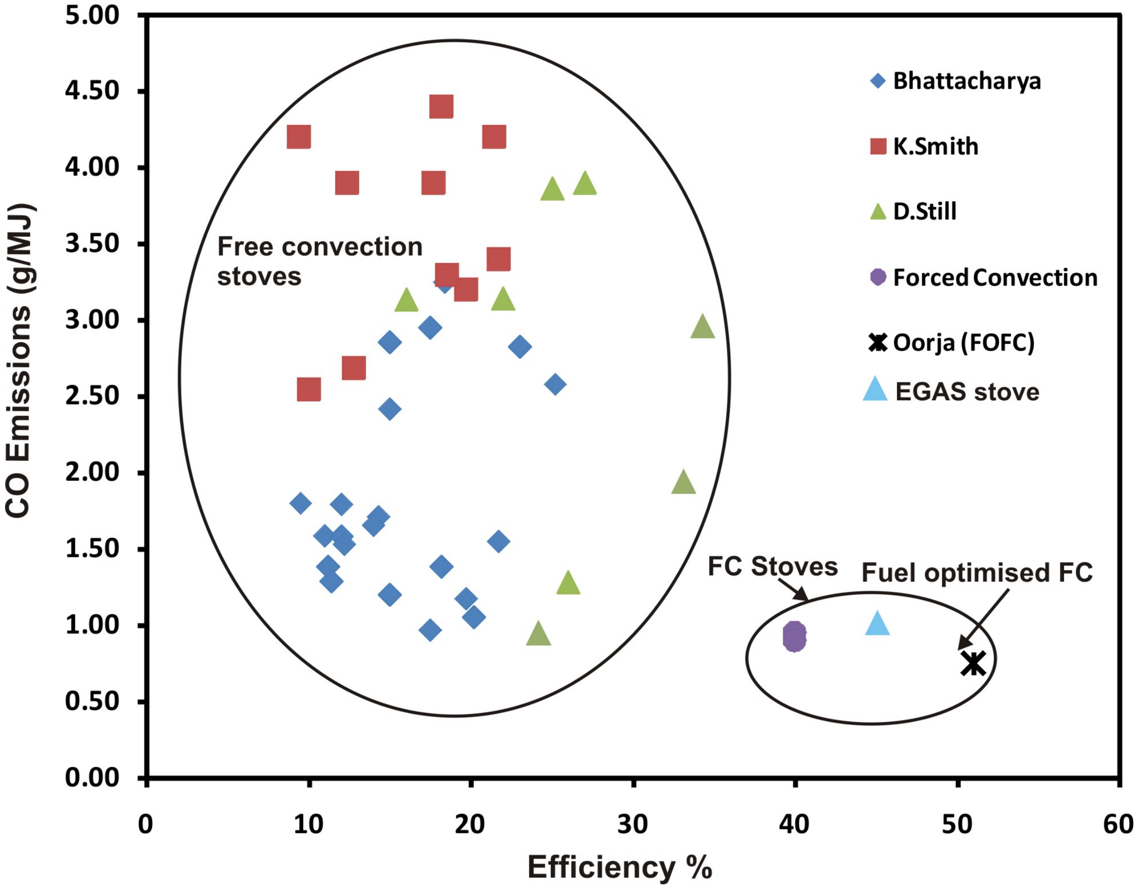

Figure 8.8: CO emissions (g/MJ) vs. water boiling efficiency from many studies

a certain arrangement of fuel sticks on the grate and tending will provide reasonably good efficiency and low emissions, it is never clear what tending will provide good results. At least sooting can be observed and controlled. However, gaseous emissions cannot be observed and hence *no observable physical control strategy* can be devised. A well controlled laboratory test may provide good performance and a whole range of field test data may indicate bad-to-average results. Rigorous protocols for testing are not of any great use since they will not represent an average user. What is amply clear from the plot is that fan based stoves that promise near stoichiometric operating conditions for combustion perform in a far superior way both with regard to efficiency and emissions. A further optimization brought about in the Oorja design relates to the choice of a high density fuel in the form of pellets. This feature is emphasized by characterizing the Oorja as a fuel optimized forced convection (FOFC) stove. The choice of high density for the fuel pellets helps reduce the volume of the combustion chamber, provides guidance as to the amount that would normally be required for cooking by needing to fill a fixed amount and reduces opportunities to obtain an inferior performance by not having to demand periodic loading or tending. Piece-by-piece loading is resorted only to extend the cooking by another ten to fifteen minutes when required rather than a basic need to do it.

Attaining high combustion efficiency appears to be a prerequisite for a “new generation” stove to not only meet the requirements of cooking, but also meet the obligations of low green house gas emissions, a fact clearly brought out by Kirk Smith in most of his writings on indoor air pollution (see for instance, Smith[23]). Keeping away from fan based designs by invoking the lack of electricity is continuously getting weakened with larger emphasis on rural electrification;

availability of electricity even for a small period during the day or night is adequate to charge the batteries used for cooking.

8.7 Summary

This chapter is concerned with a discussion of stove designs that are based on “gasifier” ideas, the theme of the previous two chapters. In the same direction of thinking, stove performance will get optimized with the use of prepared firewood pieces or an engineered “solid fuel” based on agricultural residues in the form of high density pellets. Several basic aspects of the stove and the fuel are brought out. The very high utilization efficiency as well as low emissions are a consequence of the generation of near-constant throughput of gaseous fuel due to gasification and a correct air-to-fuel ratio used for combustion of the gases. The role of secondary air in strongly controlling the CO emissions is emphasized. An alternate design that uses a throat in a horizontal fuel feed port with air drawn-in through it by an ejector action due to high speed fine jets of air in the vertical combustion chamber is also described. This design can use a variety of fuels that are prepared in terms of size and moisture reduction. This stove has performance comparable to the reverse downdraft design.

An important aspect brought out is that while free convection based stoves may be appropriate in totally unelectrified areas, forced convection stoves may be *the only way to the future* in improving the quality of the environment around the stove, apart from higher efficiency; the minimum demand on “tending” is met with by the current design.

A viewpoint that emerges from the present effort is that biomass must be brought into the mainstream by adequate preparation in terms of moisture, size and ash content. Therefore, the crucial aspect of producing adequate amounts of dense pellet fuel and making them available in an affordable manner forms the primary limiting feature in resolving the cooking fuel problem of India as well as other similar countries. Such efforts will also contributing to alleviating the problems of climate change, a subject of vigorous international debate at this time.

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9 Torrefaction and Pyrolytic oils

9.1 Introduction

Pyrolysis is a phenomenon basic to thermochemical conversion. It is the "Lysis" (breaking down) through "Pyro" (heat). No matter whether it happens in an atmosphere of an oxidant like air or in the absence of any oxidant, the phenomenon that occurs in the condensed phase will be the same. What makes the difference in the processes is related to the rate at which it occurs. There are two extremes - slow and fast. The two extremes relate to both the temperature rise rate and size. Large biomass size (say more than 10 mm) and low heating rates, typically less than 1°C/s go together much like very small size material (of less than 1 mm) and very high heating rates of 1000°C/s or more. The reason they go together is that even if the heat flux from any source - convective or radiative is high, it does not follow that the biomass will get heated up fast. The conduction process is slow because of the thermal diffusivity of biomass is small. What will happen is that the outer layers will get charred and the temperatures attained go up to 500°C, but the interior temperatures take longer to go up. The hot gases simply come out without transferring any additional heat to the system. It is useful and important to match the heating rates to benefit from the design. Thus large size objects can be dealt with only by slow heating process. When it concerns gasification or a special biomass called torrefied fuel one contemplates slow pyrolysis. However, when fine sizes are chosen, it is possible to go to high heating rates. This route is useful for producing pyrolytic oils at high conversion fractions. While the route of slow pyrolysis as applied to gasification has been discussed in detail in Chapter 6, the other two aspects, namely, torrefaction and pyrolytic oils will be discussed presently. The best way of describing the variety of the sub-products obtained with the heating rates is presented in Fig. 9.1. The four different diagrams describe the output of gas, tar and char at different heating rates with two different final temperatures – 550 and 1000°C. At very high temperatures, gas is the largest component at the highest heating rate and the lowest at very small heating rate. The magnitude of tar and char keep increasing towards the decrease of heating rates. At 550°C, the behavior is just opposite of what is noted for 1000°C. The slow pyrolysis regime belongs to gasification. Fast pyrolysis is meant for liquid generation. The medium regime may be encountered but not designed for; this is because one desires only one product - gas, char or liquid. Zanzi et al has made measurements of the yields of various components for two biomass - birch and quebracho at high temperatures. The results are presented in Table 9.1. The inferences from Table 9.1 are several. As temperature increases the gaseous component becomes very large. Different biomass have different outputs although the principal magnitudes are not very different. Amongst gases, CO occupies the highest fraction, followed by hydrogen and methane. These data are relevant when one contemplates gasification of fine biomass by fluidized bed approach. An important point to note is that the composition is sensitive to temperature (and also to particle size not shown here; can be found in Zanzi et al, 2000) as this process is controlled little by external mass transfer effects; the use of fine particle sizes bring down the process time to just the heat-up time of the entire particle.

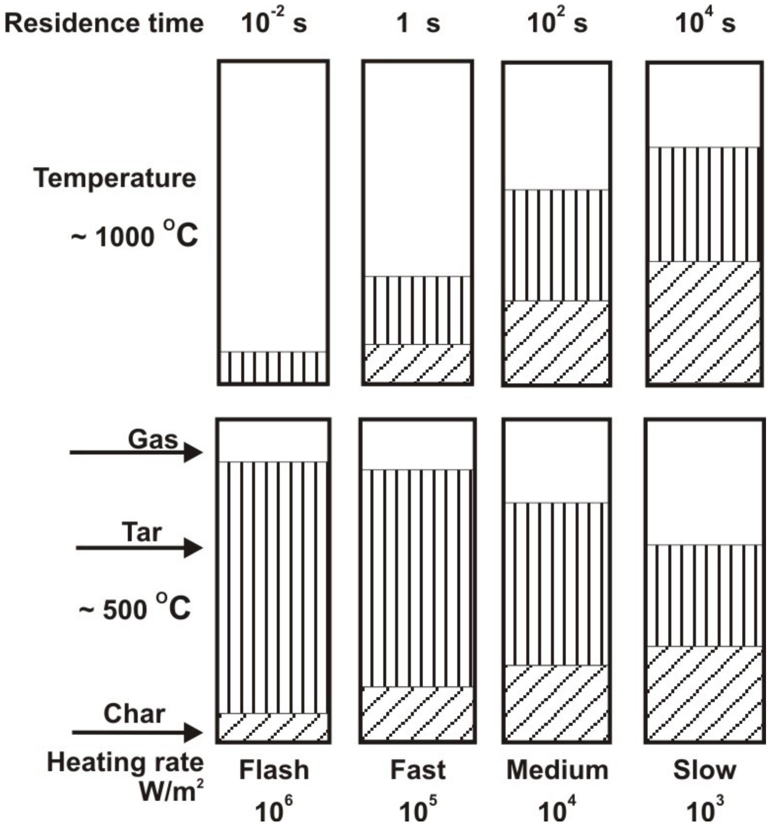

Figure 9.1: The fraction of gas, tar and char at different residence times or correponding heating rates and two temperature ranges - 550°C and 1000°C

Table 9.1: The results of rapid pyrolysis as a function of temperature for particle size of 0.5 to 1 mm for two wood types - birch and quebracho

Item	Birch	Birch	Quebracho
Temperature, °C	800	1000	800
Tar, %	1.1	0.2	1.4
Char, %	7.2	5.6	10.4
Gas, %	77.7	87.0	72.9
Water + losses, %	14.0	7.2	15.3
CO, % (v)	50.7	45.7	49.7
H_2, %	16.8	34.0	16.2
CH_4, %	16.2	11.7	17.5
CO_2, %	8.3	7.5	9.0
C_6H_6, %	1.2	0.6	1.6
C_2H_2, C_2H_4,%	6.2	0.5	5.3
C_2H_6, %	0.3	-	0.3
Toulene, %	0.3	-	0.4

9.2 Torrefaction

Torrefaction refers to a process of heating biomass uniformly to a temperature between 200 to 250°C depending on the biomass and holding at this temperature for some time so that the biomass loses about 30% dry mass through gases and volatiles. This process lends to the biomass several properties. It retains about 90% of the energy of biomass and since only 30% of mass is lost, its energy density is increased by 30% (0.9/0.7 = 1.3). It makes the material hydrophobic so that long time storage does not cause moisture absorption problems; the material is made very fragile so that it can be pulverized with much greater ease compared to the original biomass. It is still not popular since biomass as a source of energy has still not received main-stream status. One of the subsidiary advantages of this process is that once it becomes accepted by the society, its use in energy applications such as gasification ensures minimal moisture so essential to obtain high energy efficiency. Those that are considered as weeds and undesirable growth of biomass can easily be subject to this thermal treatment ensuring quality product. In such cases, odd shaped biomass can be subject to torrefaction, pulverized and then pelleted or briquetted to obtain high density. This combined process upgrades the quality of biomass and makes it more economical for transportation (a matter brought out in the earlier chapters, but acquires more importance because of enhanced energy density).

The word torrefaction appears to be a misnomer and misleading. What actually happens is the removal of some tar containing compounds. Hence, its correct name should perhaps be de-tarrification which is what occurs at the chemical level. Nevertheless the standard nomenclature is followed here. Several laboratory studies have been completed by ABETS (2006), Prins et al (2006), Bridgeman et al (2008), and Michel and Schmid (2009), ABETS performed the research at the laboratory level and developed an industrial system for bamboo. Bridgeman has done research on a number of biomass - reed canary grass, wheat straw and willow wood. Priems et al as well as Michel and Schmid on wood. But most of these studies are at laboratory scale. The details from the studies in ABETS (2006) are presented here as they correspond to a range of sizes including the industrial scale. Bamboo was chosen for the study. It is important to state why this was was chosen.

Bamboo, belonging to the class of grass grows in various parts of India on a large scale both naturally and on man-made plantations particularly in the north east. Bamboo has a typical life of 50 to 60 years and then it flowers and dies. This is a crucial period and it was estimated that the amount of bamboo that was to flower in 2005 – 2007 would amount to 4 to 6 million tonnes. It was thought fit to evolve a procedure that could help preserve the biomass for subsequent use elsewhere if necessary. The bamboo species used for experiments was Bambusa bambos, a thorny bamboo and one of the three major species of the country. Each stock weighs 3 - 3.5 kg/m and is about 2 - 2.5 m long. The first set of experiments was conducted first with small samples in an electrically heated oven with temperature controls. Figure 9.2 shows the bamboo that has gone through a thermal processing at various temperatures indicated in the photographs. It is only at 205°C that the bamboo losses its tenacity and becomes brittle, indicating torrefaction. In order to systematise the process, a 1 kg/h system was conceived. The schematic of the process is shown in Fig. 9.3. A batch type pilot plant of this capacity was built first. The heat source for torrefaction was obtained by combusting (producer gas + air) mixture in the combustor. The producer gas was generated in a gasifier system using waste wood as the feedstock. In a field system, this would happen with dry bamboo as the feed stock. The gases coming out of the torrefaction chamber were recirculated in part to ensure that the oxygen in the hot gas entering the torrefaction chamber does not exceed 3%. For otherwise, the bamboo (and for that matter, any biomass) may get into thermal runaway conditions leading to com-

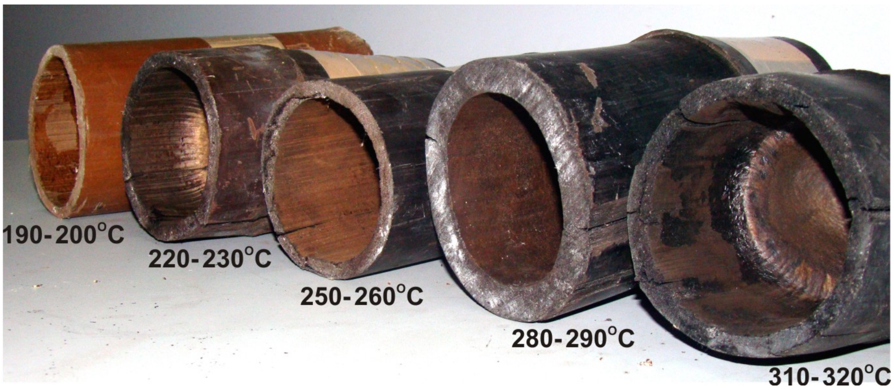

Figure 9.2: Bamboo pieces after processing at various temperatures shown and held for 2 hours each

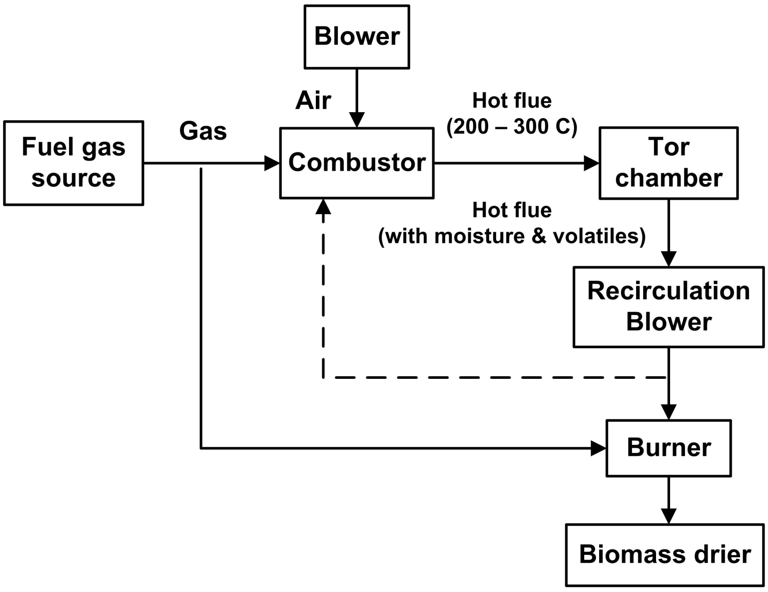

Figure 9.3: The schematic of the torrefaction system

bustion. There were initial problems of blow off of the combustion of producer gas when mixed with the dilute gas from the torrefaction chamber that were managed with a suitable design of the combustor and the mixing device and the pressures developed downstream. Also, the extent of mixing was varied during the process. Initially, till the material in the torrefaction chamber attained 100°C, moisture would be the significant component and these gases were recirculated minimally. Subsequently, the recirculation rate was increased. The gas that is not taken into the combustion chamber is exhausted. Since beyond 100°C, the gases contain obnoxious components (acetic acid and others of the kind shown in Fig. 9.5), they are burnt in a hot gas environment of producer gas flame. This ensures that the exhaust is clean. The hot gas temperature at the entry to the torrefaction chamber was maintained at 200 to 225ř C. The combustor and the torrefaction chamber are fitted with thermocouples to record the bed temperature in the chamber as well as in the bamboo cross section to determine the possible differences in the temperature. The combustor, torrefaction chamber, blower were insulated along with piping ensuring minimal heat loss.

The parameter that was to be established in the above process was the residence time. Towards this end, the bamboo that was procured had a length of about 6 m with a diameter of 80 to 100 mm at the bottom and 50 to 80 mm towards the top with a wall thickness of 10 mm. The moisture content and ash were measured as 50 and 2% on wet basis. The bamboos were sized to 0.6 m long for the experiments. The biomass consumption for generating the producer gas was about 8 kg/h in these experiments. The temperature histories of the torrefaction chamber and those inside the bamboo are shown in Fig. 9.4. As can be noted, the temperature differences are with in ± 10°C. the heat up time is about 5 hours and even though the data is shown for a duration of 10 hours, it appears adequate to operate the system for about seven hours to obtain product of quality.

While in these experiments no measurements of the composition of the gases and volatiles were made, measurements of the composition of the products made on reed canary grass from the work of Bridgeman et al (2008) is presented in Fig. 9.5. The generation of CO_2 begins early but most components are generated significantly at about 250°C. The components generated are acetaldehyde, acetic acid, formic acid, methanol, carbon monoxide and methane in the decreasing order of magnitude. As was brought out in Chapter 6, the structural fragment that makes the most contribution to torrefaction is hemicellulose that begins to degrade around these temperatures. Also some degree of depolymerization of long chain cellulose molecules and the other ring structures in lignin will occur. Based on a large number of experiments performed, the design of a continuous 50 kg/h plant that was put together is shown in Figure 9.6. A large number of experiments done on this system showed good results. The progress in the quality of the product at various temperatures is shown in Fig. 9.7. While increased temperature of thermal treatment will increase the fixed carbon content till most volatiles are removed, the torrefaction is considered appropriate if the volatile fraction comes down to around 75%.

9.3 Fast pyrolysis

Prof. Tony Bridgewater of Aston university, Birmingham, UK has shown undivided interest in fast pyrolysis processes over the last twenty five years and made significant contributions. The essentials are relatively simple. Any biomass must be dried and pulverized to fine sizes of 250 microns to about 1 mm. These are heated at a rate of at least 1000 K/s. Sometimes temperature rise rates of 10,000 K/s are the considered targets. Since the maximum temperature difference between the outer surface and the core will be about a few degrees at these heating rates, they

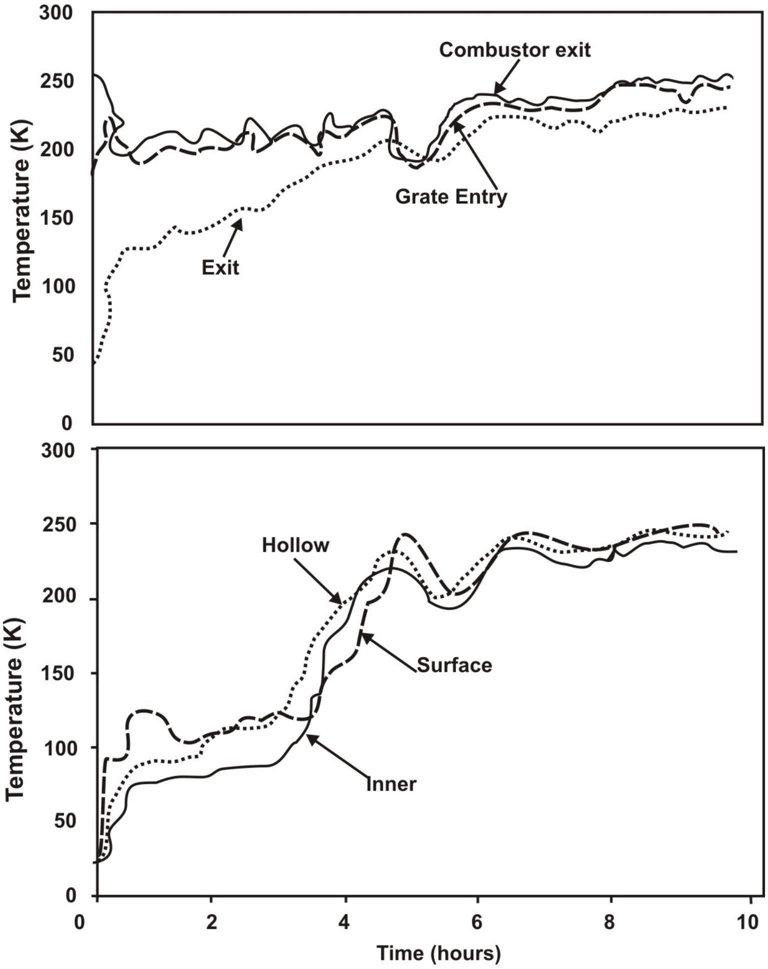

Figure 9.4: The temperature histories - Top: Furnace Combustor exit, grate entry and exit; Bottom: Temperatures of the bamboo at the outer surface, middle of the section and inside

are considered acceptable. The maximum temperature to which the material must be taken is about 500°C. The maximum residence time of the hot vapors and gases should be no more than 1 s or so. The product is immediately cooled so that any subsidiary reactions are frozen. There are also permanent gases that will pass through the system. But the fraction of condensates will turn out to be about 60 to 65%. This constitutes the pyrolytic oil. Figure 9.8 shows the plot of the yield with temperature. Clearly, there is an optimum temperature that gives the highest yield. As temperature increases from very low values, the oil production increases. But beyond a certain temperature, in this case 500°C, the decomposition of the oils produced is fast and so, the oil fractions come down. A simple model due to Liden et al (1988) explains this behavior. Several processes are used to achieve the appropriate temperature and residence time range to optimize the output. Entrained flow reactor, circulating fluid bed reactor, vortex reactor, cone reactor have been used to produce the bio-oils by different technology developers. Table 9.2 provides a summary of the processes and the performance. Table 9.2 contains the details of five different technologies which are schematically brought out in Figure 9.9.The temperatures that are deployed in all the technologies are about the same - 500 ± 20°C, except for the Twente university technology that seems higher and yet with a good output. The reason is related to the residence time. A low residence time allows the preservation of oils that have pyrolyzed. The low residence time is also the property of CFB technology used by Ensyn. The entrained bed technology experimented by Georgia Institute of Technology uses a vertical reactor tube in

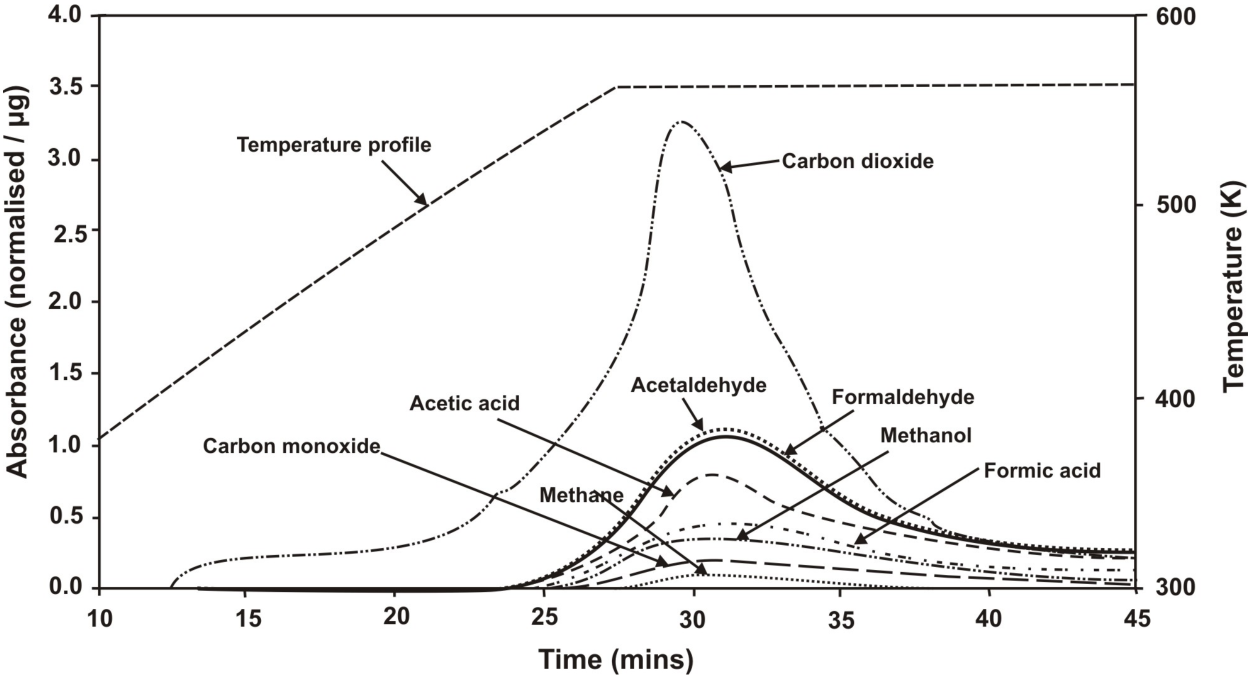

Figure 9.5: The products at various stages of torrefaction of reed canary grass, from Bridgeman et al, (2008)

Figure 9.6: A 50 kg/h torrefaction plant

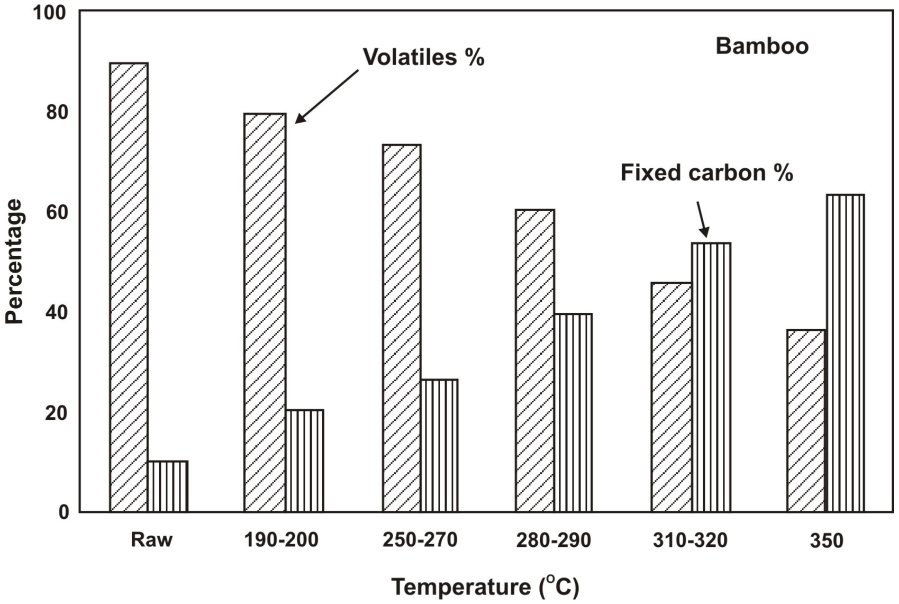

Figure 9.7: A proximate analysis of bamboo at various stages in the torrefaction process

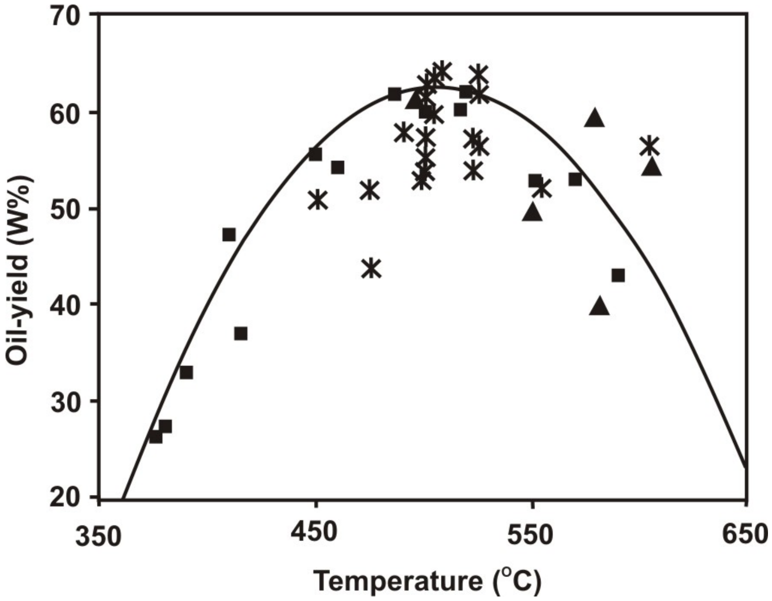

Figure 9.8: Oil yield fraction of biomass with fast pyrolyisis temperature, the line is due to Liden et al, (1988)

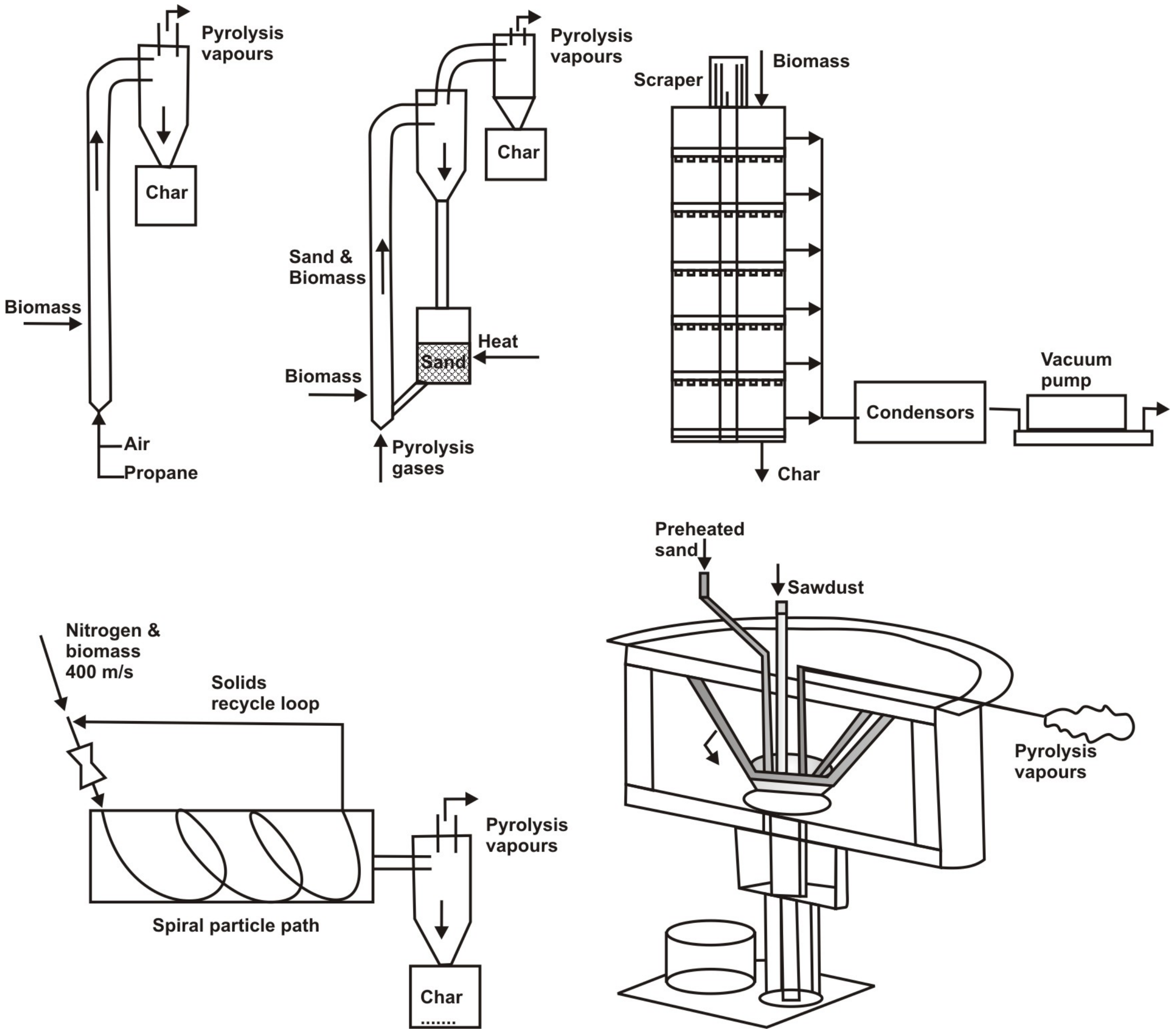

Figure 9.9: Schematics of the five pyrolitic oil producing technologies; a: top left: The entrained bed process, b: top middle: circulating fluid bed process, c: top right: The vacuum pyrolysis process; bottom left: d: The vortex process, bottom right e: The cone reactor

Table 9.2: Processes, feedstock and output properties; GIT = Georgia Institute of Technology, USA, EB = Entrained Bed Reactor; Ensyn: Canadian Company, CFB = circulating fluid bed; Laval, Canada, VP = Vacuum pyrolysis; SERI: Solar Energy Research Institute, current NREL, Vortex Reactor; RC = Rotating Cone

Institution	GIT	Ensyn	Laval	SERI	Twente uni	Unit
Technology	EB	CFB	VP	VR	RC	
Temperature	500	550	480	510	600	°C
Pressure	1	1	0.01	1	1	atm
Flow rate	500	50	30	30	12	kg/h
Biomass size	0.5	0.2	10	5	0.5	mm
Gas residence time	1.0	0.4	3	1.0	0.5	s
Solid res. time	1.0	0.4	100	1.0	0.5	s
Properties of the product						
Gas fraction	-		-	10	10	%
Char fraction	21		15	14	10	%
Comb. Liquid	53		59	66	70	%
Water-in-liquid	26		26	10	10	%
Density	1.23	1.21	1.23	1.20	1.20	kg/lit
Viscosity	10 (60)	90 (25)	5 (40)	90 (30)	80 (20)	cp (°C)
LCV	17	17	19	22	23	MJ/kg

which air and propane are burnt stoichiometrically in the bottom section of the reactor. Dry biomass powder is introduced into the upward flowing gas. The pyrolytic gas is taken out of cyclone that separates particles. M/s Ensyn technologies have deployed an upflow circulating fluid reactor. The gases themselves are used to fluidise sand that is the medium for fluidization. It is possible that the gases may not be adequate to fluidize the system. additional inert gas has to be used in such cases.

The vacuum pyrolysis process uses a multiple hearth reactor that has been studied at the University of Laval, Canada. Wood chips are fed into the top compartment of reactor and transported downwards by gravity and by the action of scrapers which are present in each compartment. If the biomass is converted completely, charcoal is drawn from bottom compartment containing charcoal. The temperature of top hearth changes from 200°C at the top to 400° towards the bottom. A vacuum pump is used to keep the reactor pressure at a value of 1 KPa.

The vortex reactor was experimented with at SERI, USA. Biomass particles are entrained in a nitrogen flow at high velocity (of about 400 m/s) and enter the reactor tube tangentially. For such condition the biomass particles experience high centrifugal forces which induce high particle ablation rates on the heated reactor wall ($\sim$ 600°C). The ablating particles leave a liquid film of bio-oil on the wall which evaporates rapidly. If the wood particles are not converted completely they would be recycled with a special solids recycle loop.

The rotating cone is another type of reactor for flash pyrolysis developed by Twente university (Fig. 9.9 e). Wood particles fed to the bottom of the rotating cone together with an excess of inert heat carrier particles of sand, They are pyrolyzed while being transported spirally upwards along the hot cone wall. The geometry of the cone used in the work is specified by a top angle of 90°. The most important feature of this technology is its high selectivity towards bio-oil and absence of diluting gas. The bio-oil yield is comparable to the yield of other high bio-oil yield production technologies. The specific features of this reactor are: rapid heating (5000 K/s) of the solids, a short residence time of the solids (0.5 s) and a small gas phase residence time (0.3 s). Since no carrier gas is needed (cost reducing) the pyrolysis products will be formed at high concentrations. If required, reduction of the gas phase volume inside of the rotating cone is possible by blocking a part of the volume inside the rotating cone; it reduces the gas phase residence time in reactor by which tar cracking in gas phase is suppressed.

Dynamotive is another company in Ontario, Canada involved in commercial fast Pyrolysis process based on bubbling fluid bed reactor. In their claims, they indicate the use of bioresidues with < 10% moisture and 1-2 mm particle size in the reactor maintained at 450 – 500°C. This temperature range is lower than in conventional fast pyrolysis systems and, therefore, has the benefit of higher overall energy conversion efficiency. The resulting gases pass into a cyclone where solid particles, char, are extracted. The gases enter a quench tower where they are quickly cooled using pyrolytic oil already made in the process. The non-condensable gases are returned to the reactor to maintain process heating. They contribute to 75% of the energy for pyrolysis. They claim to have tested over a hundred types of feedstock including plant and agricultural residues.

There are two other reactor designs that have been tried - auger and friction over a rotating hot medium. These have product characteristics not vastly different from the above ones.

The product output from all of them is between 60 to 70% liquid which has about 15 to 20% water in an azeotropic form. This prevents the separation of water. This feature contributes to the problems of Pyrolytic oil. The calorific value is about 40% of liquid hydrocarbons (and so comparable to dry wood itself). The higher water fraction contributes to difficulty in ignition allowing its use only in continuous combustion systems like gas turbines. Perhaps a cleaned pyrolytic oil can be a good fuel for a micro-turbine. It cannot be used in diesel engines directly except in a mix with diesel and it is not miscible with diesel. Only emulsions can be made. One of the other issues of the oil is its extreme acidity (pH = 2.5) making it very corrosive. The liquid has storability issues and hence has to be used in a duration of time before degradation affects the fluid properties. The way storability expresses itself is by increased viscosity. Viscosity values are much higher than diesel in three cases. The commercial process of Ensyn has a high viscosity, implying that it must be heated before being processed by the engine system. This, of course is not uncommon for fuel oil users. In respect of purity, fine carbon will get drawn into the liquid while most char may be taken out by high efficiency cyclones through which the gas stream passes through before its condensation. Fine filtration processes including centrifugal separation will be needed to get a liquid consistent with the requirement of an engine.

Currently, most of the output is being used as food flavouring agent. It can be used conveniently as a fuel to replace fuel oil in furnaces. The only constraint would be the cost of the pyrolytic oil that now has be pumped at nearly two-and-a-half times the flow rate to match the energy input. A competing process for heat generation would be gasification. The difference between the two would be either a large fixed cost with gasification systems or a larger running cost with pyrolytic oil. Usually, it is the former that is more acceptable. It appears therefore that a better alternative is as a feedstock in a biorefinery for producing hydrocarbons.

9.4 Summary

This chapter has been concerned with two pyrolytic processes – slow and fast. While slow pyrolysis is the basis of gasification, a subject addressed already in the earlier chapters, what is addressed here is a special fuel called torrefied biomass with higher energy density with hydrophobic quality and lends itself to pulverization that is less energy intensive. It can be pelleted or briquetted to help economy in transportation.

Pyrolytic oil is a result of fast pyrolysis. Pulverizing dried bioresidue to sizes less than a mm and heating the material at a thousand K/s or better to temperatures around 500°C will generate about 65% of the dry biomass as pyrolytic oil. This oil has a lower calorific value of 17 to 19 MJ/kg and has about 15% water in an azeotropic mix with oil. It has fine carbon in it that must be filtered out. Its current use as a food flavoring agent appears more commercially attractive than for energy applications.

Thus, both torrefied fuel and pyrolytic oil have to find a place in the commercial energy space.

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10 Biorefinery

10.1 Introduction

Liquid hydrocarbons are the prized commodity of any community or country today. Even if the issue of peak oil in terms of global availability that has been debated over the last decade extensively (Bardi, 2009) may be considered controversial, the actual international bid price of crude oil has been increasing from what was considered difficult-to-deal-with in 2006 at 30 USD per barrel has gone to a peak of 140 USD/barrel and is hovering around 70 USD/barrel afterwards. The countries have generally reconciled to these price rises. These prices are particularly worrying to oil importing countries like India which are also on the economic growth path. Countries like India can benefit from finding replacements for high speed diesel that has the highest consumption amongst the refined petroleum fuels and affects the economy because it is the fuel used in heavy vehicles for long distance transportation of goods. The other petroleum product, namely, gasoline is also important for light motor transport. The bioresource based replacements for gasoline and diesel are ethyl alcohol and biodiesel. Of course there are other petroleum products like kerosene and fuel oil are important in domestic and industrial sectors. If sufficient amounts of alcohol and biodiesel are produced, other strategies for kerosene and fuel oil used mostly for stationary applications can be charted. If biowastes like urban solid waste, agricultural residues, plantation residues, waste oils from hotels and refining plant oils are intended to be converted to liquid hydrocarbons, they are best accomplished if the variability of the input feedstock and the range of output products are dealt with in a wholesome manner. The output of the liquid hydrocarbons from the conversion process will also be a mix of many hydrocarbons. This mix also varies with the nature of the feedstock. Hence this process is best accomplished in a biorefinery that deals with all the aspects in a wholesome manner. Also, many types of biomass have special chemicals. Processing them to extract these chemicals would add value to the profit line as well. There are many possible routes from biomass to liquid fuels. These were described in some detail in Figs. 3.1 and 3.2. These are set out in summary form in Fig. 10.1.

There is a broad classification in these routes - First generation (1^{st} Gen) and Second generation (2^{nd} Gen) fuels. Bio-ethanol from sugarcane and bio-diesel from plant seeds belong to the first category. Bio-ethanol from starch and more appropriately, from cellulose belongs to the second category. Similarly, biodiesel from any arbitrary biomass belongs to second category. From what can be noted, one difference between the two generation technologies is the wider resource base with the 2^{nd} Gen technologies.

10.2 First Generation alcohol

The top part of the Fig. 3.2 shows the elements of conversion of sugars, starch to ethanol. The method of producing ethanol from sugarcane juice involves fermentation using yeast. It is also

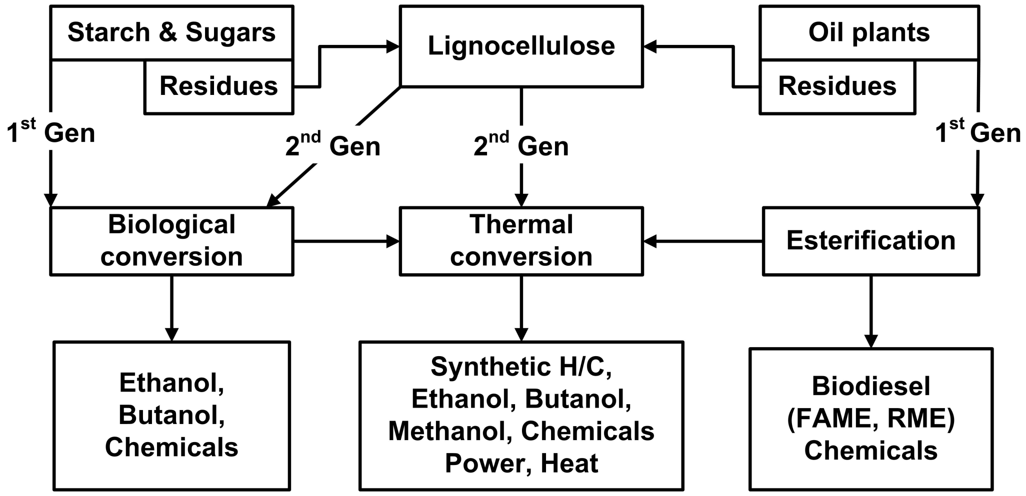

Figure 10.1: Schematics of the routes for conversion to liquid hydrocarbons

the last step in cellulosic ethanol process. Starch and cellulose will need to be converted to sugars before the yeast or other bacteria can cause fermentation to alcohol. This part is discussed below in section 10.4. In the last thirty years, much has been learnt and done on producing alcohols from sugarcane, corn and some cereals. Brazil has practiced the process to its economic advantage very significantly. Having started the program in 1975 consequent upon the Yon-Kippur war in the Middle East, Brazil has been producing alcohols from sugarcane running four million cars on pure ethanol and about six million vehicles as fuel-flex vehicles (vehicles that can use gasoline and ethanol in any ratio) with an actual user-perceived impression of being economically competitive with gasoline. Consumer prices for ethanol in Brazil, adjusted by the calorific power as related to gasoline, are 20-30% lower than gasoline.

There are issues of food vs. fuel when it concerns sugarcane; its use for ethanol implies diversion from sugar production. Corn based ethanol in the USA created diversion of a significant amount of corn for ethanol leading to rise in prices of corn based food products. Hence, most countries are aware of these issues and it is important not to create circumstances for food vs. fuel debate. This is helped by expanding the resource base to herbaceous biowaste. Further, if the emissions from production (including the fossil fuel input into the production of fertilizers) and transportation are into account, life cycle assessment from 1^{st} Gen biofuels frequently exceed those of traditional fossil fuels.

10.3 First Generation Biodiesel

The first generation biodiesel is obtained from plant oils. This subject has been discussed in section 3.2; fats and oils are essentially esters (acids bonded to alcohols). The acids are known as fatty acids and are made up of hydrocarbon chains. The fats and oils used to make biodiesel are known as triglycerides. A triglyceride means that three (tri) acids are bonded to an alcohol, in this case three fatty acids bonded to a glycerin. Fats and oils can decompose in the presence of water with heat accelerating this process. When fats and oils break down they form monoglycerides, di-glycerides and free fatty acids (FFA or Free Fatty Acids are not esters). The process of trans-esterification implies converting from one form of ester to another form of ester. The process requires reacting agent like methanol or ethanol and a catalyst like potassium hydroxide (or sodium hydroxide). During trans-esterification a basic catalyst breaks the fatty

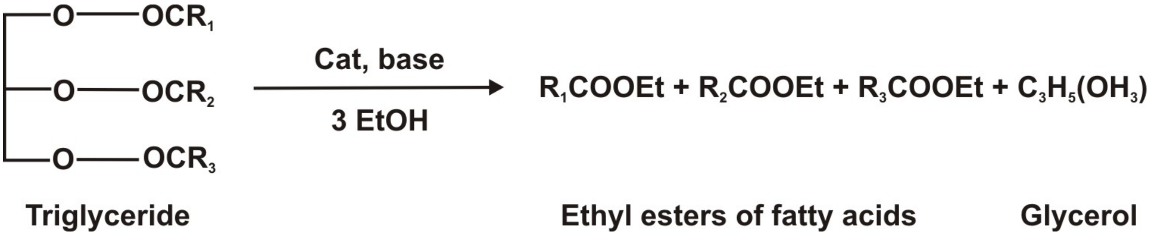

Figure 10.2: The reaction pathway from triglyceride to biodiesel

acids from the glycerin one by one. If a methanol contacts a fatty acid they will bond and form biodiesel. The hydroxyl group from the catalyst stabilizes the glycerin. Trans-esterification takes a few hours at ambient temperature and decreases at higher temperatures. The reaction of a trigliceride reacting with ethyl alcohol to produce the ethyl-ester (biodiesel) and glycerine is shown in Fig. 10.2. The technology has reached commercial market in India and other countries. The biodiesel has to meet ASTM standards in terms of properties. The principal properties are that it has about 10% less heat of combustion compared to neat diesel, it provides better lubricity, lesser emissions on most undesirable species, can be mixed with diesel to any extent required. It has been tested in most vehicles using compression ignition - buses, heavy vehicles and high power engines powering trains. The feedstock widely thought of for use are Jatropha and Pongemia. However, Palm oil needs to be factored into the production cycle if biodiesel has to make any dent on the economy. Usually any effort in this direction is saddled with food vs. fuel debate. Interestingly, the country has adequate waste lands (33 million hectares) that will enable strategies to rationally develop these into plantations for growing high output species like palm oil. These have to be pursued in a public-private partnership mode. The issue of how much energy goes into producing a fuel to the energy in the fuel has been a matter of debate. Figure 10.3 shows the output-to-input energy ratio for both alcohol and bio-diesel producing biostock, It can be seen that the energy output-to-input ratio is about 8.5 to 10 for sugarcane, between 1.5 to 2 for corn, wheat straw, sugar beet and wood. An assessment made on the energy balance in corn plants in the USA show that *most of the fossil energy consumed* in making corn ethanol goes to processing the feedstock from cooking and distilling to drying the distillers grains. In any case, it may be possible that to get a desired form of fuel, the energy put into it in other forms not capable of being deployed directly may be more and it is not necessary to argue that the energy ratio should always be favorable. To exemplify this, the energy in waste residues in a given industry may be much more than the oil used in its engine for power generation. And, it may require more energy to produce the desired form than is present in the waste. The upgraded oil will help producing energy while the waste cannot. Thus, the argument must be carefully used. Very little fossil energy is needed to make ethanol if renewable energy is used for processing (In Brazil, sugar cane waste, bagasse is used for boiler fuel. This is the explanation for the higher energy ratio for sugarcane ethanol. Ethanol from cellulose is expected to have a similar fossil energy balance (and therefore a related reduction in greenhouse gas emissions). In one assessment, cellulosic ethanol from wood residue required less than 20 percent of fossil energy to deliver a unit of energy; corn stalks required less than 10 percent (Wang and Huo, 2006). The fossil energy balance of corn ethanol will improve as corn stalks, wood waste or methane from cattle manure are used for heat in processing ethanol feedstocks instead of using fossil fuels.

In any case, sugarcane growing countries like India stand to benefit from the production of alcohols from sugarcane instead of other feed stocks. If it is needed to be done with excess food waste, it is possible to do it at high output-to-input energy ratio as long as the fuels used

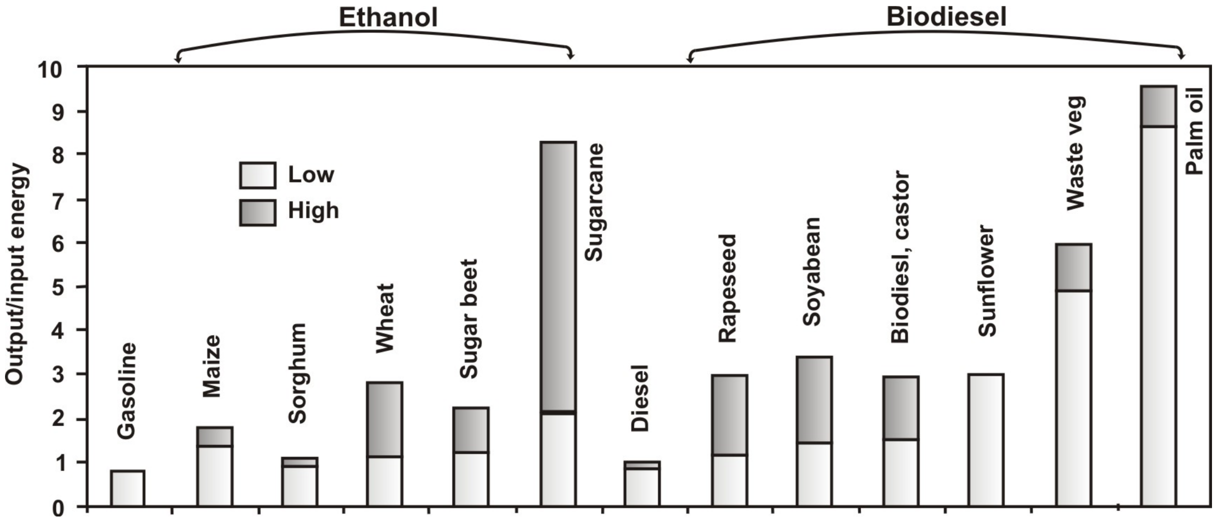

Figure 10.3: Energy output/fossil energy input ratio for producing ethanol and biodiesel respectively from various appropriate feed stocks. Note that several feed stocks like maize, wheat, sugarcane, soybeans, sunflower, palm oil constitute edible oils. Others not presented here like jatropha, pongemia are also good candidates for biodiesel and have a energy ratio between 2 and 3. Drawn from: GEF (2005)

Table 10.1: Ethanol energy consumption and balance in Brazil from Suani Coehlo (2005)

Item	Scenario-1 MJ/tc		Scenario-2 MJ/tc	
Agricultural operations	41		41	
Transportation	42		35	
Fertilizers	66		64	
Lime, herbicides, pesticides	19		19	
Seeds	6		5	
Equipment	28		28	
Sugarcane production	202		192	
Electricity	-		-	
Chemicals, Lubricants	6		6	
Buildings	12		9	
Equipment	31		25	
Ethanol production (total)	49		40	
Extrenal energy flows	Input	Output	Input	Output
Agriculture	202	-	192	-
Factory	49	-	40	-
Ethanol produced		1920		2050
Surplus bagasse		168		316
Total	251	2088	232	2366
Output:input ratio		8.3		10.2

for thermal processing utilize bio-waste itself. The way to calculate the energy output-to-input ratio involves the consideration of a whole range of components as shown in Table 10.1 drawn from Suani Coehlo (2005). In so far as bio-diesel is concerned, palm oil holds the highest value of energy output-to-input compared to other feedstocks. Jatropha and Pongemia have an output-to-input ratio of 2 – 3. A whole range of issues has been addressed by an IEA document entitled “Biofuels for transport” that also has excellent collection of references (IEA, 2004). A very useful review of the Brazilian program is presented by Suani Coelho in 2005.

10.4 The biochemical process for second generation fuel

Complete hydrolysis of starch with acid generates the monosaccharide glucose only. Incomplete hydrolysis or enzymic hydrolysis yields a mixture of glucose, maltose, and nonhydrolysed fractions called dextrins. Acid hydrolysis is conducted by adding acid to a starch slurry heated to just below its gelatinisation temperature. The most common acids used are hydrochloric and sulphuric acid. The heat separates the starch molecules sufficiently to allow the acid access into the starch granule. Once within the starch granule the acid cleaves the linkages between the dextrose molecules within the starch polymer. The reaction is neutralised and the starch filtered, washed and dried.

By cellulosic ethanol is meant a process by which cellulose present in the biomass (that also has hemicellulose and lignin) is converted into ethanol. This is more complex than starch hydrolysis because it is structurally far more complex. The first attempt at a process for ethanol from wood was done in Germany in 1898 with the help of a dilute acid by hydrolyzing it and producing about 8% of ethanol. Much has happened in the subject over the last hundred years. Acid hydrolysis has been replaced by enzymatic hydrolysis. The several stages to produce ethanol using a biological approach are (i) a "pretreatment" phase, to make the ligno-cellulosic material such as wood or straw amenable to hydrolysis, (ii) cellulose hydrolysis (cellulo-lysis) to break down the molecules into sugars, (iii) separation of the sugar solution from the residual materials, (iv) microbial fermentation of the sugar solution, and (v) distillation to get the desired concentration level. The pretreatment techniques include acid hydrolysis, steam explosion, alkaline wet oxidation, ammonia fiber expansion and others. Even though the oldest of these is acid hydrolysis, it has the problem of generating inhibitors (like furfural and other compounds) in further processes. Ammonia fiber expansion is occasionally chosen for pretreatment because there are no inhibitory side-effects. When the feedstock is wood with high lignin, these treatment processes are not the most effective. In fact the biochemical route is best suited for herbacious biowastes rather than lignacious wastes. In fact one current research area is to grow plants with much less lignin. The second process involves breaking the cellulose into sugars again through a chemical or an enzymatic route. In early times, dilute HCl or H_2SO_4 were used in processes operating over a range of pressures and temperatures. The de-crystallized cellulosic mixture of acid and sugar-in-water solution reacted to produce glucose molecules. In the enzymatic process, cellulose chains can be broken into glucose molecules by cellulase enzymes much like what happens in the stomach of bovines where the enzymes are produced by bacteria. It is in this area that research in biology to produce engineered enzymes has contributed to progress in the efficiency of ethanol production. One industrial process uses steam explosion to pre-treat the biomass and then use engineered enzymatic processes to produce the sugars. The final step of converting sugars to ethanol occurs in a fermenter, again with suitable enzymes. While traditionally, bakers yeast has long been used in brewery industry to produce ethanol from 6 carbon sugars. Since 5 carbon sugars are also present in the hydrolysate, specific microorganisms have been engineered to deal with both 5-carbon and 6-carbon sugars and help ethanol production. These processes have reached the stage of commercial demonstration with feedstock such as corn stalk, wheat straw and sugarcane bagasse.

10.5 Gasification for second generation technology

The feedstock for the gasification process can be solid fuel or pyrolytic oil or tars in the circulating fluid bed gasifier or processes that use steam alone for gasification. For small throughput,

Table 10.2: Results of tests on oxygen gasification system (from Reed and Das (1988)

Item	Test-1	Test-2	Test-3	Unit
Fuel	Wood	Wood	Wood	
Throughput	450	700	900	kg/h
Oxygen	100	150	220	kg/h
Producer gas	720	1175	1600	kg/h
Purge gas, CO_2	66	66	66	kg/h
Char	30	42	48	kg/h
Producer gas composition, volume %				
CO	39.2	44.4	45	
H_2	21.2	21.5	22.1	
CO_2	30.2	26.7	24.6	
CH_4	6.2	5.2	5.7	
C_2H_2	0.3	0.4	0.5	
C_2H_4	1.5	1.4	1.5	
C_2H_6	0.4	0.3	0.3	
C_3–	0.2	0.1	0.1	
Reactor Temp	820	820	875	°C
Gas temp	680	695	685	°C
LCV	8.5	10.8	10.0	MJ/nm^3

one can use fixed bed gasifiers. The fixed bed system is different from the one discussed in Chapter 6 where air gasification was discussed. As different from this approach, the reactive gases that need to be used for the purpose producing liquid hydrocarbons, are oxygen, steam (superheated to serve as a gas), carbon dioxide or a combination. Much effort has gone on in Europe and the USA in this area all aimed at using large throughputs with circulating fluid bed approach. Fixed beds are not contemplated in these countries as it is understood that the scale demanded is much higher. A scale of relevance in India is a throughput of about 30,000 tonnes per year (about 4 tonnes per hour) from the point of view of sustainable availability at costs that can promise final product at reasonable prices. For this class, even fixed bed systems should be capable of delivering the performance in two or three reactors. Such fixed bed based reactor designs are being pursued at IISc to generate syn-gas that contains CO, H_2, CO_2, CH_4 with some "tars". Reed and colleagues have performed research on oxygen gasification of biomass. These show a fair amount of CH_4 (of 4 to 5%) indicating to the presence of larger fraction of tars. This happens in particular because the reaction rates with oxygen are much higher and hence, they correspond to high heating rate class. And the results reported in Chapter 9 show that one generates higher condensibles at higher heating rates. The only way of reducing the tars would be to mix the oxygen with superheated steam or CO_2 and operating the system at that oxygen fraction that promises better characteristics for further processing for producing hydrocarbons. Table 10.2 shows some results from the work of Reed and Das (1988). These results show a H_2:CO ratio of 0.5 a ratio not the most appropriate for use in a Fischer-Tropsch (FT) synthesis (see below) for conversion to liquids. Perhaps the use of steam or CO_2 will generate a gas that will have H_2:CO ratio of 1 or better making the gas more suitable for the FT process.

For pyrolytic oil and tars as the feedstock, one needs to use a different type of reactor with liquid injection and a suitable oxidant (again an appropriate combination of O_2, H_2O, CO_2) supply to produce synthesis gas. Such a gas is then ready for Fischer-Tropsch synthesis.

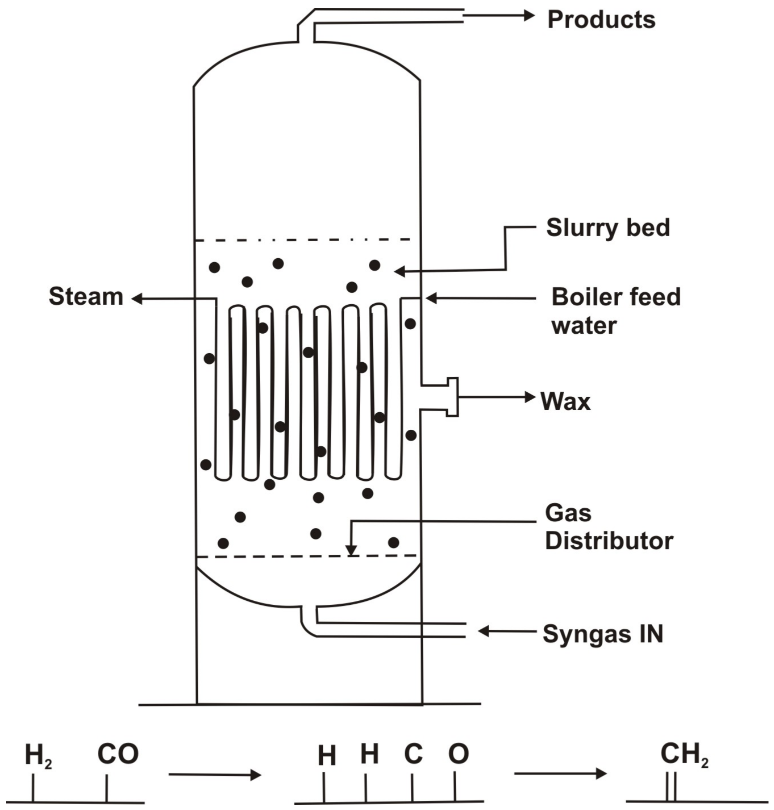

Figure 10.4: Schematics of the routes for conversion to liquid hydrocarbons

10.6 The FT process for second generation fuels

The Fischer-Tropsch process developed in Germany during world war II is perhaps the most used process and has been written upon the most in literature. It is a process of converting syn-gas to liquid hydrocarbons. Its reaction is

$$CO + 2H_2 \rightarrow -CH_2- + H_2O$$

In this reaction -CH_2- represents liquid hydrocarbon chain. It is an exothermic reaction, with a heat of reaction of -167.4 kJ/mol CO. As can be noted, this reaction has a H_2:CO ratio of about 2. Since H_2:CO is between 0.9 to 1.3 in the steam-oxygen biomass gasification process, the process should be designed to handle this variation. The reaction requires a catalyst. The properties of the catalyst will determine the product composition. Usually a mix of hydrocarbons from gasoline to methane to wax is produced. Process optimization is very simple for methane even though it is not required. However, the catalyst and the process conditions are to be optimized to produce products like diesel and wax. Figure 10.4 shows the schematic of the reactor and the way the reaction occurs on a catalyst surface.

The reactions are carried out at high pressures of 2 - 4 MPa and temperatures of 250 to 350°C. pressures of 2-4 MPa [3]. The catalysts used are Fe, Co and Ru based systems. The area of catalysts is a complex and an important one where much work has been done and still being done. It is the combination of the catalyst, pressure and temperature that control the output. The output is usually a mixture of hydrocarbons and one needs to do refining afterwards.

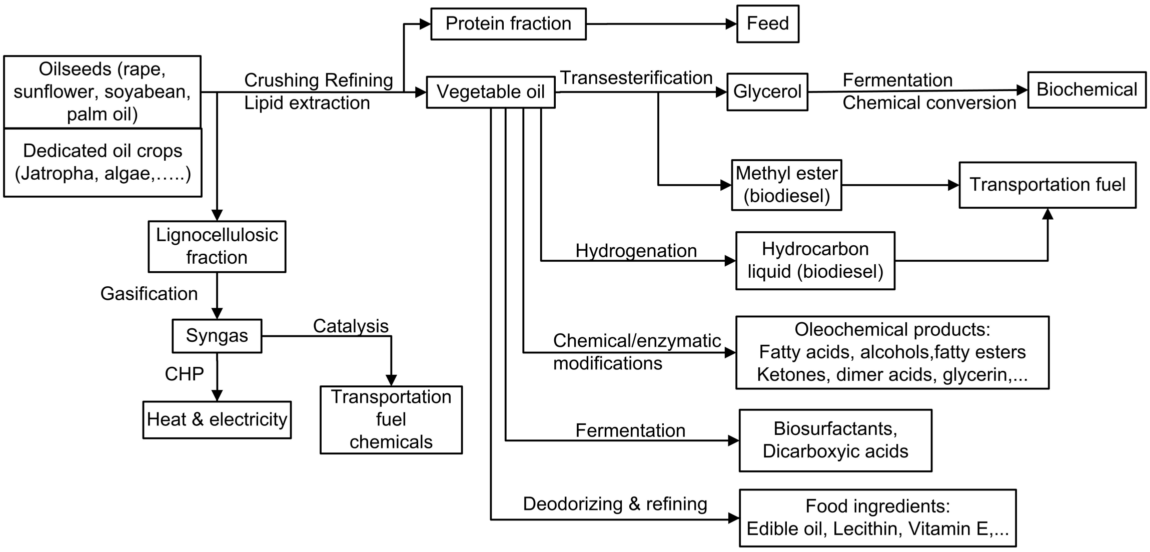

Figure 10.5: Refinery schematics for processes using oils and fats to get biodiesel, energy and chemcials

10.7 Chemicals

A strategy developed in the biomass community over the last decade, with strong interest shown in the last five years, concerns the intent to produce various chemicals from biomass. These could be co-produced with liquid fuels to enable complete utilization of the feedstock. Much thinking has gone into this strategy. An excellent report issued by NREL, USA (Aden et al, 2004) has examined the issues in great detail. This report identifies twelve building block chemicals that can be produced from sugars via biological or chemical conversions. The building blocks can be subsequently converted to a number of high-value bio-based chemicals or materials. Building block chemicals, as considered for this analysis, are molecules with multiple functional groups that possess the potential to be transformed into new families of useful molecules. The twelve sugar-based building blocks are 1,4-diacids (succinic, fumaric and malic), 2,5-furan dicarboxylic acid, 3-hydroxy propionic acid, aspartic acid, glucaric acid, glutamic acid, itaconic acid, 1,4 succinic, fumaric and malic acids, 2,5 furan dicarboxylic acid, 3 hydroxy propionic acid, aspartic acid glucaric acid, glutamic acid, itaconic acid, levulinic acid, 3-hydroxybutyrolactone, glycerol, and sorbitol xylitol/arabinitol.

10.8 Combining various routes

The way to combine producing from a variety of biofeedstock products like special foods, ethanol, biodiesel, special chemicals and electricity requires matching the output needed with the input received and equipment of a number of throughputs to optimize the operational efficiency. A few options that have been considered are shown in Figures 10.5, 10.6 and 10.7. Figure 10.5 presents a strategy that includes processing native plant oils, both edible and non-edible with that of algae. The outputs may have processed animal feed, esterified transportation fuel and other chemicals. Similarly Fig. 10.6 includes sugar plants with grasses managing the sub-processes as needed to produce ethanol and other chemicals identified therein. Figure 10.7 presents the case of paper and pulp industry wherein the outputs can be pharmaceuticals and transportation fuel in addition to paper.

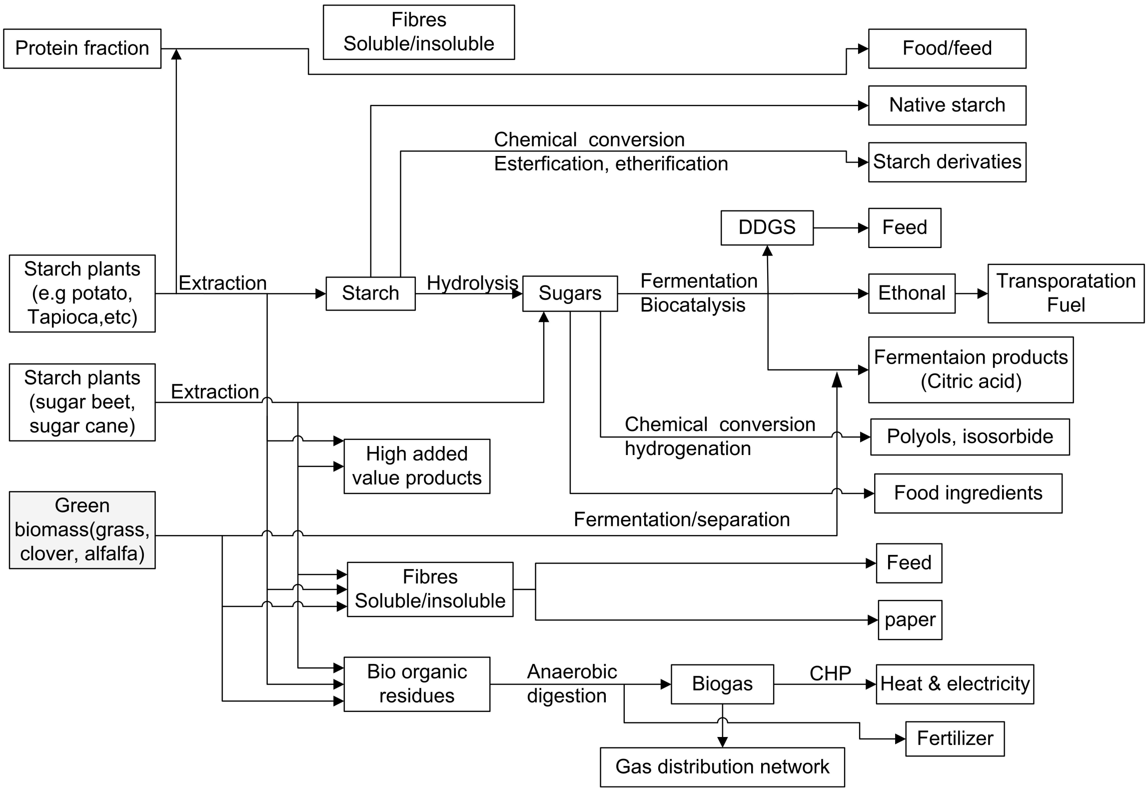

Figure 10.6: Refinery schematics for processing sugar plants with grasses to get ethanol, heat, electricity and chemicals

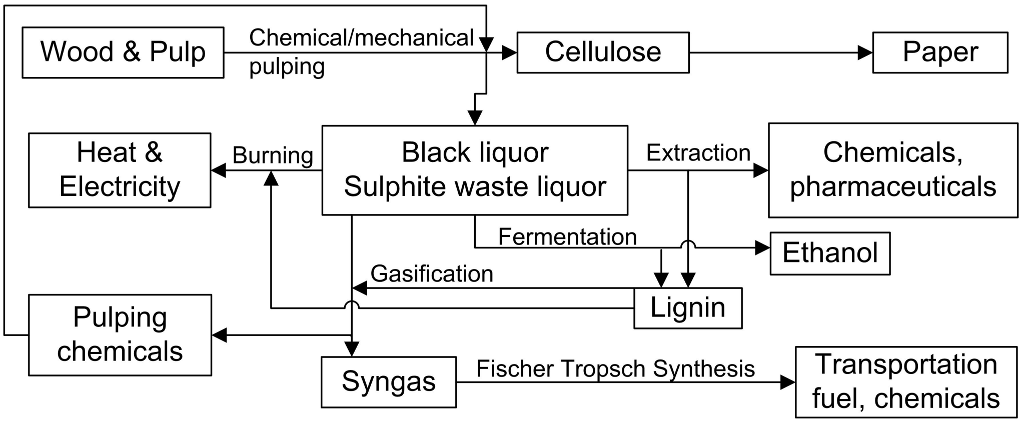

Figure 10.7: Schematics of processes in a paper industry to get many outputs - paper, chemicals and transport fuel

As can be noted, the principal transport fuels produced are ethanol and biodiesel. Discussion of biorefinery approach does not imply that these should be handled only in this manner. The plants for ethanol and biodiesel can be independently located and managed with separate battery limits. It is also possible to conceive of a large number of preprocessing units for plant oils based on the current infrastructure and have the plant oils (and other wastes, if needed) transferred to more centralized plants for upgrading the oils into esters.

10.9 Green house gas emissions

The subject of green house gas (GHG) emissions has been one of the most debated subjects since the IPCC report produced substantial evidence connecting the rise in the temperature to anthropogenic emissions of CO_2 as well as CH_4 and NO_x. The global warming potential of CH_4 is much higher than CO_2 (by 21 times, in fact). However, the crucial point of CO_2 emissions is that its half-life is in terms of 200 years where as other gases have much shorter life and methods to limit them might help mitigate long term effects something not easy with CO_2 particularly with no change in the business-as-usual (really life-as-usual) in the countries contributing to its emission. One important strategy that has come to light in recent times is that if carbon is sequestered into the soil additionally, the longevity of the sequestered carbon that appears to be very large (of the order of 500 to 1000 years) might help matters. This implies that one needs to grow biomass and periodically harvest it, use it for energy generation and the residual carbon set into the soil. In India, it has been known from folk practices that fine charcoal is used to condition the soil around coconut trees. Thus the strategy of getting oils and residual solid biomass can help create a win-win situation for energy as well as environment.

In the light of the seriousness associated with GHG emissions, much effort is made to use such fuels in such ways that GHG emissions are lowered. A particularly relevant question would be whether the use of plant oils and ethanol will reduce or enhance the emissions. In this context, one invokes the idea of wells-to-wheel emission as well life cycle assessment of emissions. The basic idea of wells-to-wheel emission is that one carefully does the accounting of the use of fossil fuel from the start to the end. For instance, all transportation of renewable biomass must account for the fossil energy if vehicles used to transport materials use fossil fuels (like diesel, or gasoline). Also if in any of the intermediate processes, one uses fossil fuel due to process requirement or convenience, it has to be accounted. Such a serious accounting has been done for 1^{st} and 2^{nd} generation biofuels as one of the efforts by UNEP (United Nations Environment Program) by Menichetti and Otto (2009). The results from this study are set out in the Table 10.3. This study has consolidated the work performed by various modelers using various assumptions on the elements in the pathway for producing the fuels. The fossil energy and GHG reduction have been indicated in the report for several studies with upper and lower values. If the best possible value can be achieved in any of the pathways, then there is enough argument for setting up standards for the plant to be built. With this thought only, the best values are shown. Several studies have shown that the use of best agronomic practices as well technology improvement can provide the best performance scenario shown in Table 10.3. The very large negative value on GHG emissions for palm oil occurs because the palm plantations were grown on rainforest that was cleared for this purpose. This is to be clearly avoided to prevent natural disasters locally as well as globally.

Corn that has been studied a great deal in the USA has shown inconsistent results. Most other feedstock seem to show substantial reductions in the fossil fuel energy used for generating the refined fuels; as also the emissions of green house gases. These are true for ethanol and

Table 10.3: The greenhouse gas emissions of first and second generation biofuels; each feedstock has been studied by at least four researchers; see Menichetti and Otte (2009)

Feedstock	Fossil energy best reduction, %	GHG best reduction, %	Comment
First generation bioethanol			
Corn	68	35	Inconsistent
Wheat	60	80	More consistent
Sugarcane	90	100	Very consistent
Sugarbeet	80	65	
First generation diesel			
Rapeseed	80	80	Consistent
Soybean	100	80	Consistent
Sunflower	100	80	Very consistent
Palm oil	65	-800	On cleared rainforest
Palm oil	65	80	Very consistent
Second generation fuels			
CE -Switchgrass	93	88	Consistent
Eth +	138	115	Consistent
BD-Lignocellulose	100	80	Very consistent

biodiesel, both for first and second generation processes.

10.10 Hydro and Super-critical gasification

By reacting pulverized biomass or steam treated fragmented biomass in supercritical water (that gets created at pressures beyond 220 atm and temperatures more than 374°C, typically 600°C) the organics are converted into fuel gases and are separated from the water phase by cooling to ambient temperature. At temperatures below the critical temperature, catalysts are required and gases that are rich in CH_4 get generated (Mozaffarian et al, 2004). But at the operating pressures of 300 atm and temperatures (600 – 650°C) H_2O becomes a strong oxidant and results in complete disintegration of the substrate structure of biomass by transfer of oxygen from water to the carbon atoms of the substrate. As a result of the high density, carbon is preferentially oxidized into CO_2 but also low concentrations of CO are formed. The hydrogen atoms of water and of the substrate are set free and form larger amounts of H_2. If the heat balance of the system has to be reasonable, one has to use a heat exchanger between the incoming reactants and outgoing products. Since tar cannot be avoided, it will inevitably deposit on the heat transfer surfaces and reduce the heat transfer coefficients. While significant efforts are being made towards production of natural gas and hydrogen in this route, several problems are yet to be overcome.

10.11 Summary

This chapter is concerned largely with liquid biofuels - ethanol and biodiesel. It is titled biorefinery because any large scale implementation that will influence the economy and preserve the environment calls for an integrated approach in which the variability of the feed stock and the multiple outputs need to be matched considering the seasonal availability of many of the feedstocks considered. As already discussed independent operations are entirely possible.

The first generation fuel technologies - ethanol from sugars and starch and biodiesel from plant oils are ready for scaling up to levels that can make a difference to the economy.of countries like India. Cellulosic ethanol technology has elements like preprocessing strategies as well as appropriate enzymes that need to be researched.

Gasification route has several pathways. The most appropriate strategy for countries like India would need to be sized at lower capacities compared to those conceived in Europe and the USA. This suggests the choice of a fixed bed system for handling the solid fuels for which research needs to deal with the combination of reactants - oxygen, steam, carbon dioxide and the details of the reactor operation to produce synthesis gas that has minimal tar like in the case of air gasification. The open top staged air injection approach offers possibilities that need to be capitalized.

Fischer-Tropsch process has always remained elusive for realization due to the economy of scale. In fact the most successful operations of coal-to-liquid and gas-to-liquid being commercially operated are by SASOL, a south African company. They use gasification-FT process to get to hydrocarbons.

It is very valuable to combine a fixed bed gasification process with FT synthesis to bring economy to scales relevant to India.

It may be important to enlarge the basket of fuels to urban solid wastes in addition to locally accessible ligno-cellulosic wastes to enable issues of fuel supply dealt with on along term basis. Growing algae for both lipids (first generation diesel) as well as a source of biomass should also be kept in mind in dealing with sustainability of the supply of feedstock.

Environmental compatibility of these approaches is not a matter of concern. These approaches are inherently “clean”. Driving the strategy for capitalizing on them can be based on the contribution to economic stability of oil importing countries like India rather than simply reducing green house gases, a major agenda in the developed world.

In both Europe and the USA gasification approaches considered are around circulating fluid bed reactors. These systems generate both light and heavy tars. The tars are condensed and then put through a gasification process separately.

Other routes like supercritical hydrogen from biomass are being pursued; they need to cross several technical challenges before they become practical.

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11 Urban solid waste (USW)

11.1 Introduction

The subject of urban solid waste has been discussed in chapter 2 while discussing sources of fuels and in chapter 5 on biomethanation route to the conversion of USW. The complexity of urban solid waste is that its composition and nature change over periods of time and location (urban or semi-urban) and the societal habits. Apart from biomass in various shapes and sizes, the composition has recyclables like iron, aluminum and other metals, plastics that can be easily separated and others that are intimately mixed. The plastics that will add energy without emission problems are the discarded polyethylene bags of various thicknesses, broken polystyrene foam packing material, discarded tires and tubes, foot wear based on polyvinyl chloride. The crucial part of dealing with urban solid waste would be to separate the recyclables to the largest extent possible. This is done by passing the material through a magnetic separator that takes away iron based articles, an eddy-current separator that takes away other metals like aluminum cans. This separation is rarely complete because the metals may be located in the waste is such a manner that unless it is disintegrated, it is not possible to separate the metals. The processing sequence is required to address this aspect.

The idea of what is recyclable is different in developing and developed countries. In developing countries like India, people with a range of economic scales manage to hold on to products with passage from the most well-to-do to segments of those living on the edge till the material is quite degraded. Also, discarded “valuable” is taken away by the rag-pickers for recycling even before the material reaches the dump site. It is sometimes argued that the energy value of the material that reaches the dump site is low enough to dis-enthuse prospective investors in waste-to-energy projects. This matter has been examined in sufficient detail at several dump sites; one of (at Mumbai) has been presented in Tables 2.11 and it is clear that the magnitude of waste with energy coming from biomass sources is significant – about 40 to 50 % of the waste throughput at the dump site.

One of the other issues with waste management is that if the collection is not done at the correct speed, partial biodegradation with start around the location where it is generated causing foul smell and poor aesthetic conditions. While this is not to be permitted, it happens because the responsibility for waste collection and delivery to the dump site is most usually with the municipal authority and the waste-to-energy project investor or manager has little to do with this segment. The further problem that arises is that the waste that is delivered to the site has to be immediately dealt with to preserve the quality of environment of the waste treatment facility. Quite often these standards are still not in place in India and the degraded environment causes problems of undesirable conditions for the habitats around the facility leading to protests and closure of the waste treatment facility. All these have happened several times in some cities in India without adequate learning, yet.

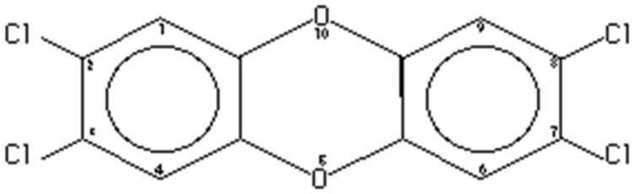

Figure 11.1: The structure of dioxin

11.2 The technical questions

We can treat the segregated urban solid waste that carries the energy as composed of biomass, plastics which are largely based on H and C elements (like polyethylene and polystyrene) and those like tires and footwear which contain elements like chlorine and sulfur. Biomass that has moisture between 20 to 60% needs to be dried and separated from sand and grit as much as possible. The plastics that do not have chlorine or sulfur will add energy and need to be sized or made into fine pieces to enable integration with biomass. The issues with plastics that contain chlorine or sulfur are more fundamental. The combustion of such plastics with oxygen will produce in small quantities compounds that contain chlorine, oxygen and carbon. The most toxic of these compounds is called dioxin whose structure is shown in Fig. 11.1. Dioxin is also technically termed 2,3,7,8-tetrachlorodibenzo-p-dioxin, the numbers 2, 3, 7 and 8 referring to the locations on the structure where chlorine atom is attached to the ring structure as in Fig. 11.1. As can be noted it has also 2 oxygen atoms. Pure 2,3,7,8-TCDD was synthesized in 1968. It is a white, micro-crystalline solid (looks like table salt) which is insoluble in water and sparingly soluble in some organic solvents. Its molecular formula is $C_{12}H_4C_{14}0_2$. Its melting point is 305 °C. The reasons for serious concern on dioxin are because it is stated to be carcinogenic (Huff et al, 1991). It appears that soils also have some background of dioxins but incineration is suggested to lead to larger emissions. Measurements of dioxin levels have been made on many waste incineration systems used with boiler–steam power generation units and a strange behavior has been observed in the measurements. Measurements showed lower dioxins at the stack inlet than at the exit; but on careful study, it was found that dioxin deposited on the stack (because it would deposit at temperatures below 305°C to varying amounts till it exited at about 150 -170 °C) was peeled off when the deposition was large enough and some of it would come off at one time in large amounts. There are limits to the amount permitted to be emitted and these are in nanograms per MJ. The problems were considered very serious in the 1990's but have been addressed through the nineties and methods to limit the emissions have been implemented.

One standard technique has been to pass the gases through a bed of activated carbon. This absorbs dioxins, acid gases and other undesirable gaseous compounds. The used activated carbon gets back into thermal treatment process to ensure the destruction of these compounds within the battery limits of the treatment facility. Dioxins can also be removed from gases through absorption/adsorption in a polymer material. One technology (ADIOX) uses polypropylene (PP) doped with carbon particles (see Zwart, 2009). The process is based on the high affinity of dioxins to carbon - when in contact, the bond between dioxins and carbon is very strong. By dispersing small particles of carbon in PP a dioxin molecule present in the flue gas is first absorbed into the PP, where it migrates to a carbon particle, on which it is very strongly adsorbed (connected to its surface). The plastic material acts as a selective filter with a preference for molecules like dioxin. Another alternative for the technology based on carbon

Table 11.1: Emissions from large MSW incinerators, drawn from USEPA (2002); TEQ = Toxic Equivalent Quantity

Pollutant	1990 Emission	2000 Emission	Unit	Reduction %
Dioxins/furans. TEQ	4.26	0.012	kg/year	99.7
Mercury	45.2	2.2	t/year	95.1
Cadmium	4.75	0.33	t/year	93.0
Lead	52.1	4.76	t/year	90.9
Particulates	6930	707	t/year	89.8
HCl	46900	2672	t/year	94.3
SO_2	30700	4076	t/year	86.7
NO_x	56400	46500	t/year	17.6

adsorption is catalytic destruction of dioxin compounds. For flue gases, this is a commercially available technology. This system termed CRI uses a specially developed catalyst to convert dioxins in the presence of oxygen to a mixture of H_2O, CO2 and HCl. The specific CRI dioxin destruction catalyst operates at temperatures around 160°C. Dioxin removal straight from the producer gas (with no oxygen present) is not possible with this catalyst.

The dioxin problem created such a scare among the public in the mid eighties to mid nineties that USEPA (United States Environmental Protection Agency) took many measures to monitor and tighten the emissions of dioxins and also other heavy metals. The magnitude of this effort became so serious that several facilities could not continue to function due to greater demands on investments with perhaps little margin. New facilities came up and these have performed over the last two decades at levels of emission performance comparable to or better than coal power stations. Table 11.1 shows the change in emissions per year between in 1990 and 2000. While the performance of the reduction is outstanding on those with high focus, the performance on NO_x emissions has been poor. Many technologies for removing NO_x have been developed during this period and they have not found a place in the treatment process, perhaps because of non-stringency of demand.

11.3 Conversion Technologies

A description of the conversion technologies related to anaerobic digestion (AD plants) has been described in chapter 5. What will be addressed here are the thermo-chemical conversion processes taking note of the discussion on several process details on combustion in chapter 4 and on gasification in chapter 6.

The processes are grouped largely as direct combustion–steam generation (for power) and gasification–internal combustion engine routed power generation (reciprocating engines or gas turbines). Even in these approaches, there are variations in details of the processes. Most of these utilize sufficient preprocessing to get energy carrying matter and one process, namely, thermoselect technologies treats the as-received waste directly. Nielssen et al (1996) have presented an excellent report on a techno-economic evaluation of various processes being developed in this period. Table 11.2 presents several of the technologies discussed in the above report.

There are five of the technologies shown in Table 11.2. There are both combustion and gasification based processes. Most of them demand preprocessing of the waste into pellets before use in the systems. Thermoselect technologies is the only one that uses the waste in as-received form involving the only step of separation of useful recyclables as a part of the process. In

Table 11.2: Thermal treatment technologies for MSW; BFB = Bubbling Fluid Bed; CFB = Circulating Fluid Bed; C = Combustor; G = Gasifier; 1 = Lime spray absorber; 2 = Fabric filter, 3 = Activated carbon injection; 4 = Scrubbing for acid gases; 5 = Selective non-catalytic Reduction; 6 = Scrubbing for particulate matter

Technology Provider	Process	Air emission Control	Water effluent control	Residue treatment
EPI, Inc	BFBC	1 + 2 + 3 + 5	Dry system	Landfill
TPS	CFBG	4 + 6	Scrubber liq. clean-up	Landfill
Thermoselect	Raw-waste O_2 – G	3 + 4 + 6 Vitrification	Metal precipitation + Distillation	Sale or Land fill
Battele	CFBG + C	4 + 6	Scrubber liq. Clean-up	Landfill
Nippon-steel	Enriched-air Gasifier – C	2 + Smelter + Granulator	Dry system	Sale or Landfill

these technologies, environmental compliance is provided higher emphasis and part off-loading of costs occurs through tipping fees paid by the municipality or the people themselves. A way to deal with such problems is to raise the temperature to melt levels of most materials so that the residue flows out. Some separation into glasses and metals can be made after quenching the melt and the residue can be sold or laid out in landfills. The fact that the metals and inorganic material has to be melted implies that the temperatures have to be raised to over 1500°C. This requires the use of oxygen as in Thermoselect technologies process or oxygen enrichment as in Nippon steel system. Many of these technologies are elegant but very expensive. In fact, the Japanese government has made investments into these plants with specific understanding that these plants be located close to the area where the waste is generated. This has implied the conceptualization of plants with small throughputs – 1.5 to 2 t/hr even though many technologies have also addressed the requirements at 30 – 50 t/hr capacity. In fact in a few locations (Hiroshima is cited as an example, see Ptyler, 2007), one stream is remaining idle for a long period. This approach must be contrasted with that taken in India where most municipalities want the investors to come in on build-own-operate (BOO) principle when sale of electricity is state controlled to a degree that makes these plants commercially unviable. Unless waste to energy plants are made profitable for the electricity generated or any other output (like fuel pellets). A few of the processes will be described now. The thermoselect process is shown in Fig. 11.2. The raw waste is compressed to high densities, as high as 800 kg/m^3. This process heats up the biomass as well. Some volatilization starts even as the "briquette" enters the high temperature environment. Oxygen is introduced in two zones – the bottom and top sections of the feed zone. The top part contributes to the gasification process involving the reaction of the volatiles with oxygen raising the temperature to 1200°C with residence times of about 4 s to ensure the break-down of complex chemicals. The bottom section has a mix of reactions, some of which lead to the oxidation of char and others leading to release of heat and melting of the inorganics and metals. The liquid will flow down into a quench area where solid fused material gets formed. The high temperature gas is quench-cooled from 1200 to 70°C to suppress the generation of dioxins to a very low value. The cooled gas undergoes additional treatment to eliminate particulate matter and acid gases before being led into the reciprocating engines. The gas has a composition of H_2 = 32.4%, CO = 43.1% and CO_2 = 18.8%. Thermoselect process–Jenbacher engine combination is in operation at several locations in Japan (see the discussion in chapter 7, section 7.7) at power levels of 1.8 to 7.5 MWe. Also there are several plants in Japan with waste conversion facilities of 1.5 to 4 t/hr capacity (Ptyler, 2007).

Another expensive technology being practiced is the plasma gasification based conversion. Two methods in practice in plasma gasification (a) plasma arc and (b) plasma torch.

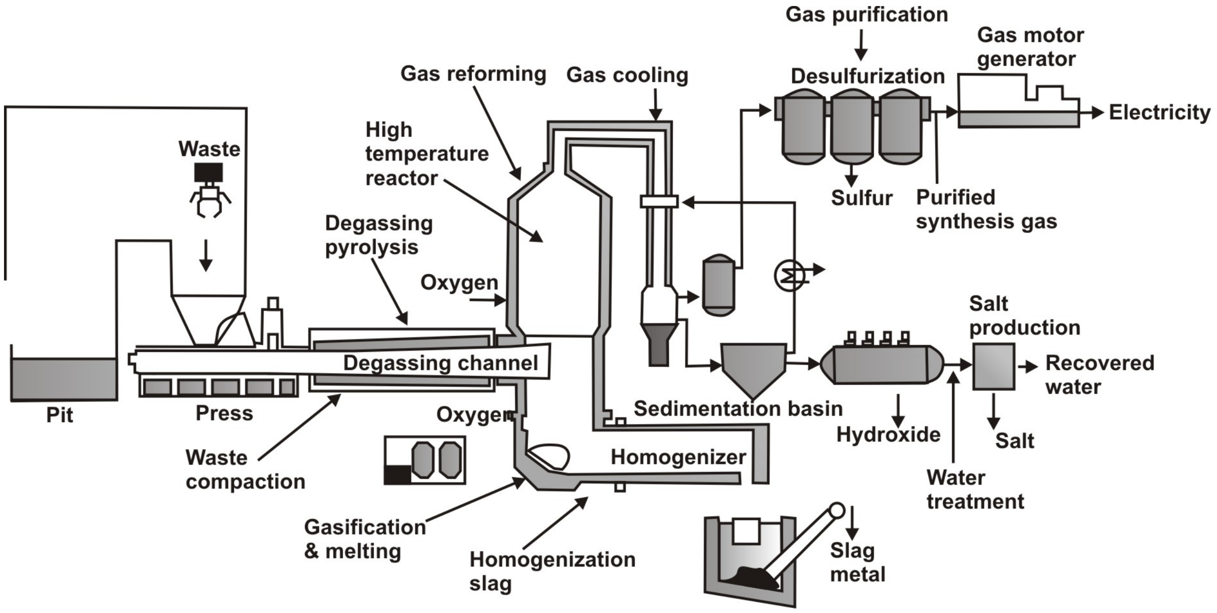

Figure 11.2: The schematic layout of Thermoselect process

The plasma arc process uses principles similar to an arc-welding machine, where an electrical arc is struck between two electrodes. The arc is generated using carbon electrodes in a bath of molten slag with the plasma arc being in an enclosed chamber. The high-energy arc creates a high temperature, highly ionized gas. Waste material is fed into the chamber and the intense heat of the plasma breaks down organic molecules into their elemental form. In zones where the temperature drops down, these react to form CO, CO_2 and H_2 and other gases. Solids such as glass and metals are melted to form vitrified mass in which toxic metals are encapsulated. The advantage of the plasma process is its very high destruction efficiency on any waste with minimal or no pretreatment. The carbon electrodes are consumable and need to be replaced or continuously inserted into the chamber.

In plasma torch process, an arc is struck between a copper electrode and either a bath of molten slag or another electrode of opposite polarity. The peak temperatures attained here could be lower and they can be maintained in part by the injection of an oxidant into the system. This will help reduce the electricity consumption of the process.

The key aspect of the plasma processes is the cost of operations. Due to significant internal electricity consumption (that can go up to 25% of electricity generated in small systems) and the cost of electrodes, it is appropriate for medical and hazardous wastes and will be far more expensive than other approaches for urban solid waste. The technologies discussed for MSW in Niessen et al (1996) does not include the plasma process perhaps because their developments for waste treatment were in early stages. In any case, its impact on waste-to-energy scene in India will remain marginal for a long time since even more economically viable systems have yet to penetrate the market in a commercially significant manner.

Table 11.3: Emissions from several waste-to-energy facilities; mg/nm^3; dioxin* includes furon and units are in pg/nm^3; all emissions set at 7%O$_2$ in the exhaust

Technology	PM	Dioxin*	HCl	HF	NO	CO	SO$_2$	Cd	Pb	Hg
EPI, Inc	13	0.1	120	0.5	150	1	30			
TPS	3 – 7	13	0.6 – 2	0.1	300	5	15	0.003	0.005	0.05
Thermoselect	0.84	0.001	-	-	21	3	0.2	0.001	0.013	0.002
US-Limit	27	60	35	-	200	100	30	0.04	0.50	0.08

11.4 Performance of the conversion systems

Performance is assessed in terms of output produced per unit input (tonne waste) and emissions. An excellent study by Alternate Resource Incorporated (ARI, 2008) has compared the technologies on the basis of meeting a requirement for a facility in Santa Barbara, CA, USA. The electric output per tonne waste processed presented in this report varies between 230 kWh to 1230 kWh/tonne waste processed. It is difficult to appreciate the value of the assessment by this route. A simple approach to this can be worked out from the understanding derived from chapter 7. A rule of thumb is 1000 kWh per tonne dry wood. High efficiency systems can go up to 1100 kWh/kg dry wood. If the calorific value of the dry waste is much higher, say, 22 to 25 MJ/kg because of the presence of plastics in the waste the conversion could be as much as 1200 to 1300 kWh/tonne waste. What this implies is that the dry fraction of biodegradable waste in the as-received waste is all that matters. If this quantity is 40 % of the as-received waste that the electricity output will be 250 kWh per tonne waste. The gas-to-electricity efficiency is a more certain value and is about 35 to 38% at larger power levels $\sim$ 1 MWe.

The emissions from these systems will be a crucial issue. The results of the emissions in various technologies are set out in Table 11.3 (see Niessem et al, 1996). Many technologies meet most requirements and in some cases at levels achieved are much lower than the allowed limits.

11.5 Options for developing countries

The range of thermochemical conversion technologies developed in the USA and Europe have had problems with public opinion that created untoward effects on the development. This has had also fall-out in India. The opposition to thermal conversion techniques has been counter productive. Added to this is the attitude of the Government and municipal bodies thinking that private enterprise will solve the problem through allocation of land and a few other infrastructural facilities. Both have not borne fruit over the last two decades. For reasons that are unclear, the simple idea of generation based incentive with payments on per kWh basis that make commercial sense have not been even thought of.

The current costs of installation of such technologies from overseas will be at 2500 to 2700 USD per kWe. For Indian conditions this may translate to 1800 to 2000 USD per kWe considering an average fraction of usable wastes from the delivered material. The electricity tariff is state-controlled in ways that are seen as risk by investors. One way out of this fluid situation is to produce quality output that can be marketed independently. Fuel in the form of pellets or briquettes are always sought after by industries. This does not imply that the products produced at varying quality will be accepted by the market. It is important to devote efforts to sanitise the in-feed, process it and produce stable, robust pellets and briquettes with specified levels of ash and calorific value, these being typically ash $<$ 10% and calorific value 16 to

18 MJ/kg. The production process needs power and this can be generated through fixed bed gasifiers along with engine described in chapters 6 and 7 to power levels that are needed for the process. While grid up-linking and related aspects can all be put in place, the economy of operation will be weakly affected on the vagaries of state policies.

11.6 Summary

This chapter has been concerned with urban solid waste, USW (or municipal solid waste, MSW) conversion technologies. The novel thermal processes are described here. Pyrolysis, gasification and combustion technologies with overlapping ideas have been used to develop the technologies. The crucial elements of most technologies would be to separate the recyclables and transfer the organics for waste treatment. Two broad approaches here are: those that introduce oxygen or highly enriched air to melt the remaining inorganic material consisting of sand, grit and glass and metals that escaped the separation process and those that tolerate it in the conversion process and dispose off the ash into landfill. The latter method is more economical and can be adopted as long as environmental regulations do not demand that the inorganic waste be vitrified.

An alternate method in which the end product could be a combination of pellets or briquettes and electricity in which the former could be a significant fraction to ensure stable market revenues.

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12 Other technologies

12.1 Stirling engines

Stirling engines are external combustion engines with over 300 years of history. Many kinds of Stirling engines have been tried out. These engines enjoy higher theoretical efficiencies than internal combustion engines at small power. This requires the use of a working fluid like hydrogen or helium at high pressures. So many engines have been built and tried out without much success. In fact the number of failed companies is large. It is only in aerospace or military applications that they have found successful use. While there are claims of producing them for civilian power generation applications in large numbers, they have not been widely accepted. The key issue is that hydrogen is a very small molecule and leakages from the system are difficult to eliminate. Even the concepts of design for ensuring long term performance in field conditions need to be carefully worked out and perhaps the lack of commercial success may be related to this.

While natural gas is a fuel around which practical systems are contemplated, some developments have examined gasification systems as well. However, it might be possible to deploy simpler combustion systems like the ejector induced gasification systems for delivering the heat to the heater head. Pursuing these directions will be possible only when a robust Stirling engine is available for packing a power generation system. A company named STM Power, Inc in the USA has claimed the commercial availability of a 55 kWe Stirling engine with a fuel-to-electricity efficiency of 31%. Its integration with a biomass based combustion system is yet to take place.

The development of micro-portable power generation systems with performance comparable to batteries have been sought in recent times. This is because liquid fuels, fossil or renewable have much higher energy densities (35 to 45 MJ/kg) in comparison to batteries that have a energy density of 1.2 to 1.3 MJ/kg. Also, of course, not all the energy present in the battery can be extracted. Even if the conversion efficiencies of thermal engines is no more than 5%, the power output will be much larger than of batteries. Gomez et al (2007) have addressed the question of micro-Stirling engine development. This uses a catalytic combustor with JP-8 as the fuel aimed at generating 42 We at a fuel-to-electricity efficiency of 22%. The total system weight is 1.7 kg excluding fuel tank and has a total volume of 2.6 liters. One can expect more such developments in coming times that will create a boot-strapping effect on the development of larger power systems.

12.2 Thermoelectrics

Thermoelectric based on Seebeck effect, the basis of thermocouples. When a set of special materials is brought together into intimate contact (at atomic level) and a temperature difference is established between the junction and the two other ends, an electric current will flow. The

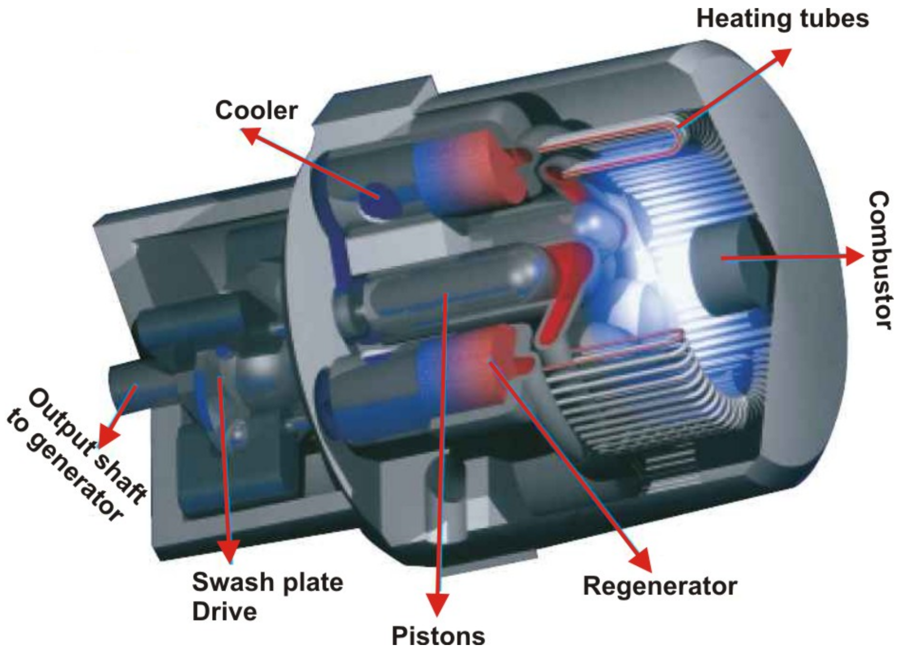

Figure 12.1: The cut-away view of STM Power stirling engine, with permission

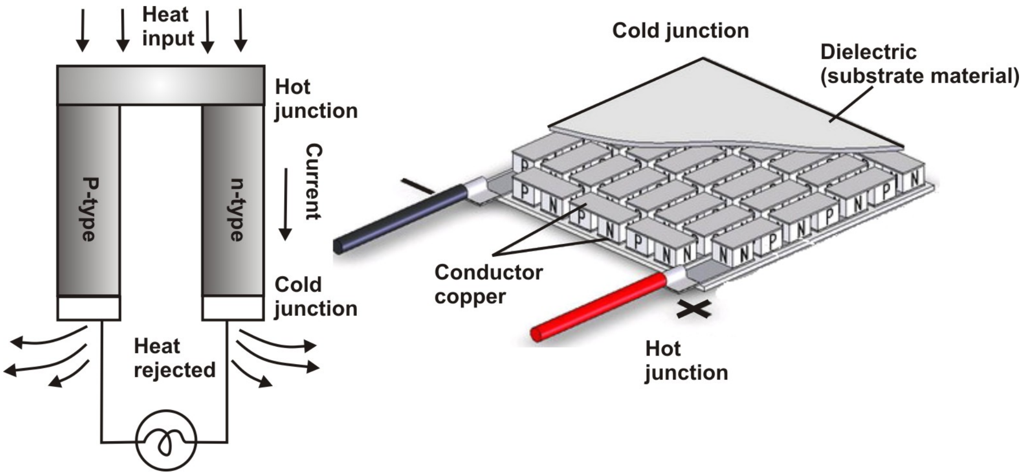

Figure 12.2: The principles of themocouple effect and a packaged thermoelectric device; the headers at the top and the bottom combine the thermocouples in series with hot and cold ends - top and bottom

voltage developed is correlated to the temperature difference. By coupling a large number of the thermocouples in series, and establishing the temperature difference, we can use this to draw power. This is the basis of thermoelectric devices. If we take Chromel-Alumel thermocouple, we have a performance coefficient of 20 mV for 800°C. Thus if we need 12 V output we need to put in 600 thermocouples. Let us assume that these are connected in series. The cost and system performance optimization requires that the length of the thermocouples be small - say 15 mm. This means that while one end is maintained at 1000°C, the other end should be at 25°C or lower. Maintaining the cold junction temperature will become an important issue then. Figure 12.2 shows the simple sketch showing the principle of thermoelectric effect and a device. The voltage (V_{oc}) measured under open circuit conditions produced can be taken to be proportional to the temperature difference (ΔT) as $V_{oc} = S\Delta T$ where S is the device Seebeck coefficient. When power is drawn from the device, the output voltage becomes about half the

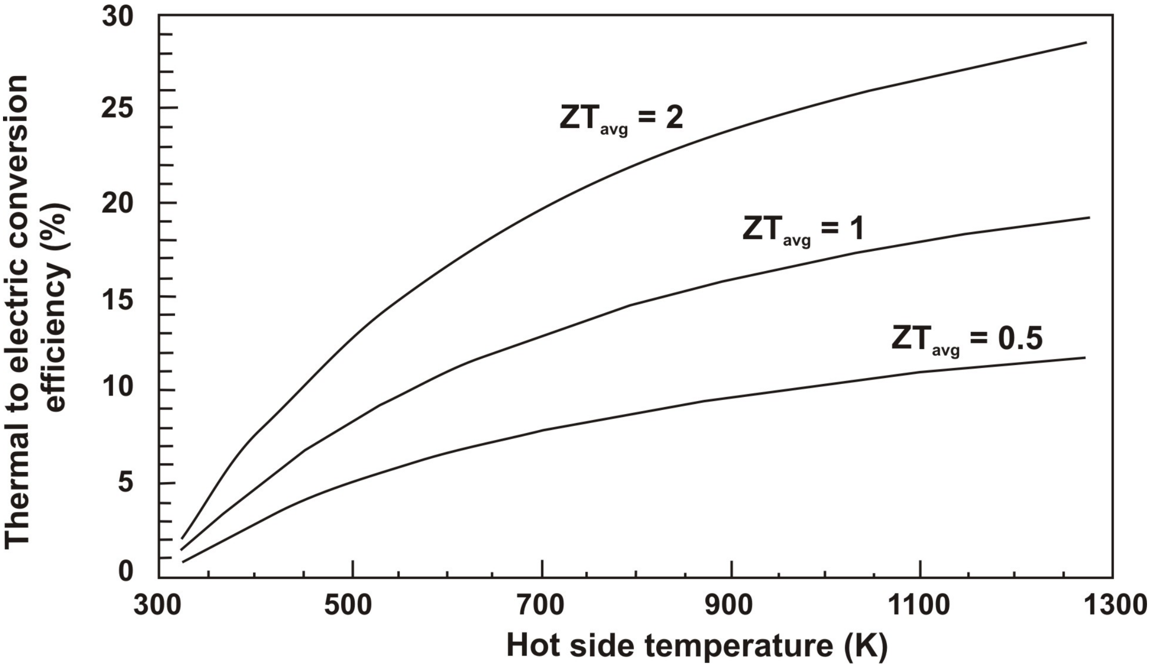

Figure 12.3: Efficiency of thermoelectric device with difference in temperature across the device for various materials; ZT = 0.5 (current practice), 0.9 (state-of-the-art), 1.3 - 1.5 (the best)

Ohmic voltage drop due to the internal resistance of the device. Therefore the maximum output power, P_{max} = V^2/R = V_{oc}^2/4R = S^2 ΔT^2/4R. Thus the maximum power output is strongly dependent on ΔT. An analysis of the efficiency of the device is worked out as

$$\eta_{ted} = [1 - \frac{T_{cold}}{T_{hot}}]\frac{\sqrt{1+ZT}-1}{\sqrt{1+ZT}+T_{cold}/T_{hot}} \tag{12.1}$$

where η_{ted} is the efficiency of the thermoelectric device, $Z = \alpha^2/k\rho$, α is the Seeback coefficient, k = thermal conductivity and ρ is the density of the material. Assuming an average temperature for T in ZT, the values for materials used in current practice, state-of-the-art and the best materials are 0.5, 0.9 and 1.5. For these values at a ΔT of 1000 K will lead to efficiencies of 11, 18 and 28% respectively. These values are very reasonable from a practical view point. Thus thermoelectric generators are worth building particularly with medium quality ZT material based system coupled to a low cost heat source, like a gasifier based biomass stove (of the kind described in Chapter 8) to produce electricity of low power domestic applications typically of about 100 W.

12.3 Algae

Lipids can be broadly defined as any fat-soluble (hydrophobic) naturally-occurring molecules. The term is more-specifically used to refer to fatty-acids and their derivatives (including mono and di- and tri-glycerides and phospho-lipids). By subjecting them to an esterification process, one can get biodiesel with specifications that allow use in reciprocating engines. Vegetable oils can also be subjected to low temperature pyrolysis to obtain biofuels very similar to the chemical composition of diesel oil.

Algae are a source of lipids and saccharides. They are microscopic single cell aquatic plants containing lipids and fatty acids as membrane components, storage products, metabolites and sources of energy. Like terrestrial plants algae need water, light and carbon dioxide for their growth. They contain any where between 2% and 40% of lipids/oils by weight. In terms of photosynthetic yields, indeed algae far outweigh the terrestrial crops in biomass production. They can be grown at a high rate of 20 – 22 gm/m^2/day which is equivalent to 73 tonne/ha/year. For this reason, species selection is made carefully and molecular biology techniques are used to enhance accumulation of more lipids (the fatty matter) than what are synthesized under normal conditions. These are done by subjecting them to stress either by way of depleting certain nutrients or temperature outside the ideal range or combination of many such parameters. Hence, one cannot expect the same yield under stressed condition as compared to the natural state of growth. This fact is not often recognized when quoting the productivity numbers. Under stress the yield may drop down by 50% or even more. This brings down the output to an acceptable value of 40 tonne/ha/year. At a lipid fraction of 30% (of which 80% may result as biodiesel) the potential to produce biodiesel is around 10 ton/ha which in itself is substantially large compared to other methods of producing biodiesel (the best production from palm tree is about 5 tonnes/ha/yr). This is the reason why several private agencies are investing substantial amounts of money into research and development (Solazyme, LiveFuels. Greenstar, Solix, Aurora biofuels and Petro biofuels are the more known companies).

There are two technologies - open ponds and photo-bioreactors. While photo-bioreactors promise appropriate conditions for the growth of the algae, they are far too expensive and one company, “Greenfuel technologies” that originated from MIT, USA had to close down the operations four years after the start. Except Solix that also uses photo-bioreactors, most others use open ponds and use ways to control the amount of sunlight received by the ponds containing the algae. The suggested argument is that the optimum sunlight required is to be provided uniformly to the extent permitted by the natural environment. The crucial element is the use of specific strains tolerant to changes in concentrations, temperature and solar energy input to enable sustained growth. While many companies grow mono-cultures of algae, sometimes genetically modified strains, one company “LiveFuels” uses an interesting idea that for decades, widespread run-off of fertilizers and other agricultural wastes into waterways has caused large, fast-growing blooms of algae in the ocean. This company grows a mix of native algae species in low-cost, open-water systems. Thus, algae is grown and harvested in estuarine environments, at the intersection of rivers carrying agricultural waste nutrients and the open ocean, in order to capture the energy and resources of the algal blooms that already occur at these locations.

There are three known methods to extract the oil from oilseeds, and these methods should apply equally well for algae too: (a) expeller or press (b) hexane solvent oil extraction and (c) supercritical fluid extraction.

The subject of algae as a source of lipids and biodiesel has yet to show commercial performance. Clearly, many approaches that optimize the processes need to be undertaken in coming times. Most of the effort is now concentrated in the USA.

12.4 Direct carbon and microbial fuel cells

Fuel cells were discussed in chapter 7 as a power generating system from producer gas (see section 7.12).

It was also pointed out that the direct carbon fuel cell (DCFC) has the potential of very

Table 12.1: Summary of the work on DCFC; M-Carb = Molten Carbonate; YSZ = Yttria-stabilized Zirconia; Li-ated = Lithiated; LSM* = Strontium doped lanthanum manganite or others used in SOFC; SRI = Stanford Research International; SARA = Scientific Applications and Research Associates

Item	Energy Source	SRI	SARA	CellTech Power	Hawaii University
Fuel	de-ashed Coke	Raw Coal	Coke	Raw/gasified Coal	Biomass Charcoal
Anode	Fuel + M-Carb	Coal + M M-Carb	Metal basket coal+ MCarb	Sn/SnO_2 melt	Char-block
Electrolyte	Mcarb	YSZ	Ni + 2% Ti	YSZ	KOH melt
Cathode	Li-ated NiO	LSM*	Molten alkali	LSM	Ag for expt
Current R & D Status	5-cell stack at 100 W studied	6-Cathode tubes in M-Carb	one 2-chamber Cell with some electrolytes	Concepts for coal use	Single KOH cell at 220°C

high efficiency of conversion from fuel-to-electricity and the possibility of using carbon from a variety of biosources. Its history is not as well known as other technologies. Dr. William Jacques patented in 1896 – Method of converting potential energy of carbon into electricity – in the USA. It was not possible to reproduce the performance for a long time until this was done with certainty only in the mid-seventies. The reasons for the non-reproducibility have been speculated as the presence of Ti in the Iron that was used to construct the cell (Jaques had obtained the iron from Norway and that may have got Ti in it).

The DCFC technology is being examined for research and development in the USA primarily, but also in Europe and Japan. The research teams from the USA are from Akron University, CellTech Power, Contained Energy, Direct Carbon Technologies, Scientific Applications & Research Associates (SARA), SRI, and the University of Hawaii. They have all concentrated on coal derived coke, raw coal and biomass charcoal. The summary of the principal elements of the approaches of several of them is presented in Table 12.1 drawn from the excellent report by Wolk et al (2007). The developments presented in Table 12.1 can be set into three broad categories, depending on the type of electrolyte used (a) with a molten carbonate electrolyte, (b) molten hydroxide electrolyte and (c) with YSZ-based olid electrolyte. The developments have been discussed extensively in a fuel cell workshop in the USA and all the presentations are available (see NETL, 2005). Figures 12.4 shows the schematics and photographs of systems under development by Celltech power and SARA. Molten carbonate electrolytes combine high conductivity with good stability when CO_2 is present; they also have the correct melt temperature for this application. The cell voltage is formed at the anode side and consumed at the cathode side, and there is an influence on the cell voltage by this partial pressure.

Molten hydroxides as electrolytes have a high ionic conductivity and a known high activity of the carbon electrochemical oxidation in which the reaction is $CO_2 \rightarrow$ 4 electrons per C atom This helps operation at temperatures of 600°C. During carbon electro-oxidation in this type of fuel cell, there is the formation of carbonates because both chemical and an electro-chemical processes can occur. If however, water mole fraction, X_{H2O} is high implying acidic (hydrated) melt, the $X_{O_2^-}$ is low and so, $X_{CO_3^{2-}}$ is low demonstrated at SARA and speculated as helped in the presence of oxides(like those of Mg, Sb, Si; MgO was already demonstrated by Jacques) and in the presence of oxy-anions (pyrophosphate and persulfate). This fuel cell uses a pure graphite cylindrical rod, which acts as the anode and the fuel. The cell is fed humidified air through a gas distributor in the bottom of the container.

The aim in using Yttria-Stabilized Zirconia (YSZ) design is to benefit from advances in the SOFC and MCFC technologies. Their components include a U-tube consisting of a metal mesh

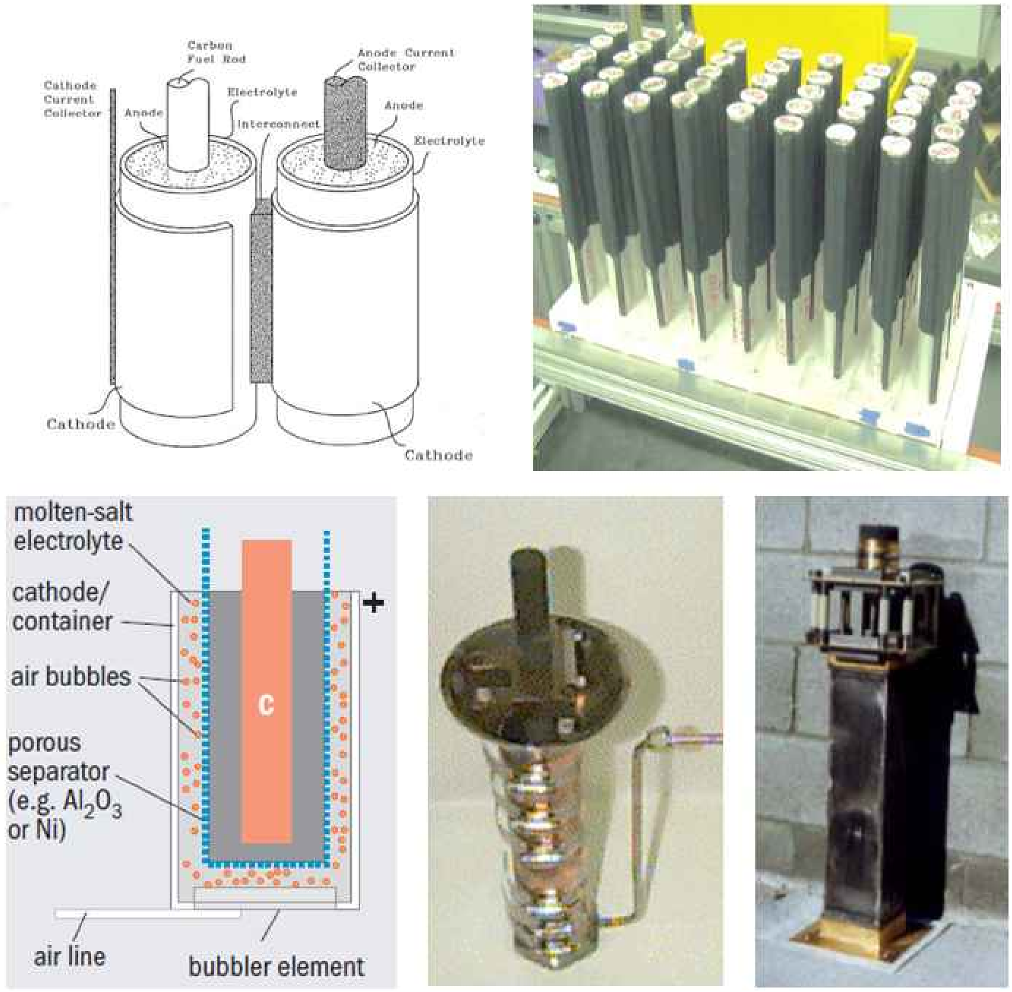

Figure 12.4: The systems under development and testing by M/s CellTech power and SARA. The two prototypes of SARA have cell area of 28 and 450 cm^2 and rated at currents of 8 and 40 amps the open circuit voltage being 0.75 V

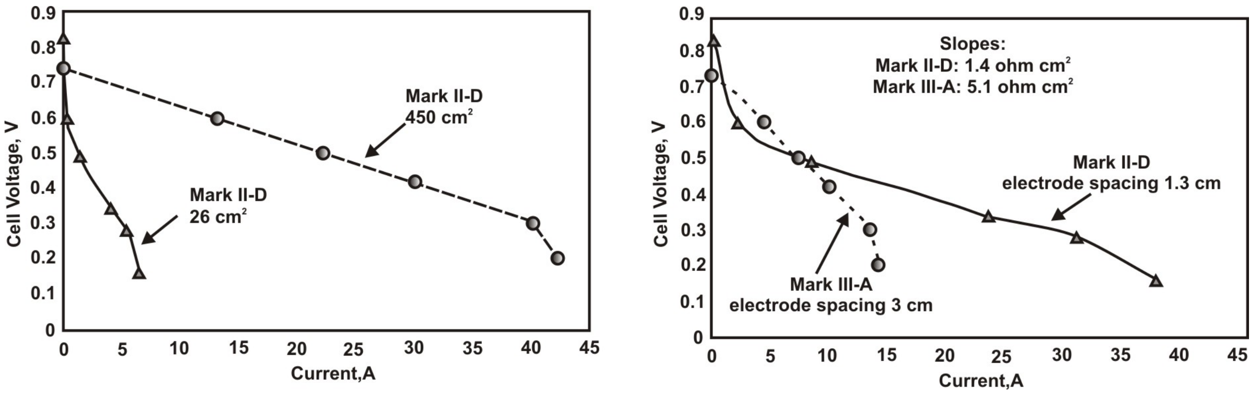

Figure 12.5: The performance of a typical DCFC – the SARA design – both Voltage-current and Votage-current density characteristics

cathode current collector, a cathode layer, an electrolyte later, and a metal mesh anode current collector. This structure is immersed into a liquid anode made of a mixture of molten elements and carbon particles. When this mixture is stirred causing a flow mode, the fuel cell operates better since there is an increased contact between the carbon particles and the anode current collector, which enhances mass transport. Figure 12.5 shows the voltage - current and current density characteristics of SARA design. The open circuit voltage (OCV) is the cell voltage at zero current, which is 0.75 to 0.8 V. This design has been tested by Hackett (2006) and the performance described in Hackett et al (2007). The behavior of the variation of the voltage at various loads (currents) has features that are quite characteristic of fuel cells. The initial decrease is due to the activation resistance. The voltage then falls less rapidly, and more linearly, and is due to ohmic resistance. There is usually a higher current density at which the voltage falls more rapidly, and is due to mass transport resistance. Smaller cells have a larger current density and larger cells have a larger current capability. In the first region, where the initial decrease is slightly steeper, the electrochemical reactions are slow at the electrode surface. When current densities are small, then the voltage losses are dominated by the slowness of the electrochemical reactions. This is called activation resistance. This is voltage lost in driving the chemical reaction that transfers the electrons to or from the electrode.

In the second, more linear region, the ohmic resistance of the fuel cell is controlling. This region also has activation losses but it is dominated by the fact that the fuel cell has some resistance. This resistance is mostly found in the electrolyte and electrodes of the fuel cell. When the ohmic resistance is high, ionic and electronic conduction is hindered, which lowers the cell voltage. Electrons will travel more slowly through the fuel cell and more heat will be generated. The rest of these losses can be found in the electrode material and the interconnections of the cell.

In the third, much steeper region, the reactants cannot get to the reaction site quickly enough due to the so-called mass transport or diffusion resistance. If the reactants cannot get to the reaction site fast enough, then the rate of the electrochemical reactions is once again limited, due to the low concentration of reactant at the electrode surface. At very high current densities, more reactant has to be supplied so that more electrons can be generated. The difference in the curves is explained by the relative ease of the transport of reactants.

In the specific design of SARA, the average output power was about 15 W over 500+ hours with peak output of 50 W for 5 to 10s. The current rating was 250 W/cm^2 in one of the latest designs reported in 2005. The efficiency as measured for the version tested was 60%. It is expected that when optimized, this value would reach 70% or more.

12.4.1 Microbial fuel cells (MFC)

Microbial fuel cells use bacteria to move the ions and electrons between the electrodes to generate electricity. They consist of anode and cathode compartments separated by a proton exchange membrane. In the anode compartment, fuel component of the water that may consist of various types of sugars, acetates or a mix of several compounds is oxidized by microorganisms, generating electrons and protons. The electrons are transferred to the anode through a mediator or a specifically identified bacteria capable of direct transfer to the anode. Then the electrons move through an external circuit to the cathode. In mediator based system, one needs use somewhat expensive chemicals like humic acid, methylene blue and neutral red (Wiki-mfc, 2010). In mediator-less systems, electrochemically active bacteria are used to transfer electrons to the electrode (electrons are carried directly from the bacterial respiratory enzyme to the electrode). One such iron reducing bacteria is “Shewanella putrefaciens” whose inoculation help direct transfer of electrons to the anode (Kim et al, 1999a) and helps reduce the operational cost.

The cathode compartment has a fluid is saturated with oxygen by bubbling air in the fluid. The hydrogen ion generated in the anode region passes through the proton exchange membrane into the cathodic region to get oxidized to water along with the electrons arriving via the electrode. The two electrodes are at different potentials (about 0.5 V)and hence, create a fuel cell. The power output from this cell varies from about 100 mW/m^2 for waste waters to 300 mW/m^2 for acetate/starch and such substrates. The performance of this cell is about is much lower than the other classes of fuel cells and effort is underway to improve its performance (Liu et al, 2004).

12.5 Hydrogen from biomass

Hydrogen can be obtained from biomass through the gasification route using oxygen-steam combination. The gas mixture has the smallest molecule, namely, hydrogen and can be separated from other permanent gases, CO, CO_2 with a small amount of CH_4. This can be accomplished by using pressure swing adsorption system or a membrane separation system. The pressure swing adsorption technique depends on the use of molecular sieve and is a well known industrial technology. The membrane separation system is also known in the literature and some aspects are still being researched to improve the purity of hydrogen extracted.

12.6 Summary

This chapter is concerned with several technologies that have been in existence for a long time and yet have not found their place in the commercial energy scenario.

The external combustion technology, namely Stirling engine has great promise but in reality it is far more complex than an internal combustion engine. What matters in engineering design ultimately is its robustness in performance. Small external effects should lead to “small” consequences as perceived by the user. The internal combustion engine is so well understood that in difficult terrains, users disassemble the engine, move it, assemble it and operate it. While it is not expected that every device should match this demand, the long term performance of

Stirling engines has not matched up to expectations yet. If the engine shows good performance with fossil fuels, finding a replacement for continuous operation with a biomass combustion device can be accomplished relatively easily.

Many rural environments are still deprived of electricity. The magnitude of this quality-of-life electricity is not large - about 200 W over a day with energy demand of 400 Wh. If a larger system that can service the demands is made available, no alternative need be found. However, such a condition is unavailable, systems to service single houses will be the only alternative. This is fulfilled by Solar photovoltaic system generally, The question is: would it be possible to develop a thermoelectric device with a biomass based continuous combustion system? Such attempts need to be made; this would imply revival of an old technology.

Algae has been discussed as a source of biomass for a long time. While it has been a subject of considerable attention in the USA with enormous financial inputs, its progress is not yet commensurate with the technical and financial inputs. This has raised concerns about the commercial viability of algae being a source of energy to reach meaningful proportions.

Direct carbon fuel cell is a biomass based route to generate electricity at the highest possible efficiency in energy conversion approaches. Here again, much effort has been put in the USA. Much has been understood, but it has yet to reach the stage of commercial relevance. Microbial fuel cells are argued to be a good alternative to treat waste waters. Their development needs to be carried out to improve their power performance and costs.

Hydrogen is needed for fuel cells for transport applications. When the fuel cells become commercially relevant, the fuel should become available. It is possible to obtain hydrogen from biomass through gasification route. Again one needs to examine the commercial viability of this approach. From what has been examined at IISc, this aspect seems a reasonable expectation.

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13 Historical notes

In March 1981, at the lunch of the "Court Meeting" of IISc, one of my senior colleagues, Prof. A.K.N. Reddy, then, a professor in inorganic and physical chemistry, a well known authority on rural technologies who started ASTRA and KSCST, spoke to me and enquired if I could start the work on gasification to replace the diesel used in pump sets as much as possible. He stated that he would send a copy of the SERI translation of Swedish work on gasification. I stated that I would accept provided Prof. U. Shrinivasa who was at that time at the Department of Aerospace Engineering would also agree to work on the project. After a number of discussions, a proposal was made for financial support to KSCST. This was sanctioned (for some Rs. 40,000) and the work got started along the design of the closed top WW II class system. This work progressed slowly for the next four years. A design different from WW II type, discarding the WWII design because it was clear that fat top had no thermodynamic role – just to hold fuel for some period of time. We argued that this looked silly and we should argue the purpose of each element. It was obvious that no such argument existed for this fat size. The L/D of the system was altered and a sleek cylinder was chosen. The top had a water seal based cover that would be opened when fuel feeding was required. It was also thought some regenerative heating could be achieved by passing the hot gases from gasification around the inner cylinder to transfer the heat into the fuel bed. This would improve the reliability of operation. We still had one problem – use of throat. The life of this throat posed serious problems. We experimented with a replaceable throat. Performance was not for sure proper all the time. This was worrisome. We had not uncovered at that time the "true" importance of drying the feed stock. We decided that we would live with this design at this time in so far as the requirements of MNES were concerned and examine possible change later in time. Only four systems were built.

It was July 1985, three years into R&D on biomass gasification. Most of the work was confined to the laboratory. We had our share of successes – a lots of rediscoveries. Backed by studies on combustion a rigorous – experimental and computation – with one very important paper on wood combustion at the International Symposium on Combustion at University of Michigan, USA and with a clear understanding that the written word on the subject was neither greatly accurate or complete or even definitive, a large number of experiments was being carried out on all kinds of ideas improvised based on the experiences on configurations in the literature.

A letter was received from Dr. O.P. Vimal inviting me for a committee meeting to be held at the Department of Non-conventional Energy Sources (DNES). Dr. O.P. Vimal was the Director of Bioenergy section. I was neither aware of him or his background at the time the meeting was called. I met with other gasification people of the country – Prof. P.P.Parikh, from IIT Bombay and Prof. P. D. Grover of IIT, New Delhi and Dr. B. C. Jain of M/s Jyothi Company, Baroda (then).

The idea was to discuss the developments in gasification. At this meeting, I was asked if we could supply some number of systems for field trials on power generation from biomass in dual-fuel mode. I enthusiastically asserted a "Yes".

Some six months later, I received a long well worked, provocative letter from Dr. K.K. Singh, a PSO at the then Department of Non-conventional Energy Sources, New Delhi, inviting me for a possible meeting. I complemented him on an unusual well worded letter not expected from a traditional government department and enquired whether he meant all that was stated in the letter about how the programme needed to be scaled up and what kind of major initiative that IISc could undertake, etc. Instead of responding to me directly, he shot a question at me as to how sure were we about the quality of the gas in terms of tar because there was considerable concern on the possibility of running engines in dual-fuel mode in a reliable way. I indicated that we had done this for several hours at a stretch and in one special experiment we ran on 1 kWe gas engine coupled to a pump for 24 hours continuously. He pushed me hard – could stand up to a strong demand to set up several field systems and provide a suitable demonstration of the systems.

I indicated that we could hold a meeting of all distinguished people at the Institute some time in about six months and hold discussions on various aspects after a demonstration of our "know-how". This was broadly agreed and I returned to IISc with minor trepidation in any mind about the problem of throat in the reactor.

A set of engineering students came to do projects at the laboratory that had moved from the main Aerospace Building to "Rocket Test House" that was desolated and hardly did anybody visit the area At this time, a paper by Dr. T.B. Reed was located by a colleague and I happened to browse through it. It talked of an open cylindrical design much like we had, but the top was open and had no throat. It had a grate, though. We decided that this suited our purpose regarding the problems of throat. It was better it was dispensed with rather than have it. It turned out later that our ignorance had prevented us from dispensing with it. Very quickly a mild steel sheet based hardware was built at the lab and tested out. The two hour run that actually burnt up the hardware turned out to be so superior in the thermodynamic performance with stable flame seen at the burner (there were no gas composition measurement facilities at the lab. In fact, most crucial research was done in the absence of it. It was only to prove it to "outsiders" that these measurements were made seven years later).

Thus the design of the hardware got altered. The reactor was simply a double cylindrical configuration with an air nozzle towards the bottom. The air nozzle though the inner shell. The earlier hardware was used by suitably altering it. The closed top with a water seal was simply altered by keeping the top cap opened all the time the system was operating. This design of air flow from the top as well as from the air nozzle called open-top – reburn design is some thing that has remarkable properties in terms of tar reduction not understood or realized till much later – after 1994-95 when the results of rigorous test at IISc and Chatel-St-Denis (Switzerland) came in due to collaborative efforts with Swiss scientists through Dr. Hari Sharan of DASAG.

I had remarked that early work was characterized by rediscoveries. The above set of results are new discoveries - not rediscoveries; so far no body else had used staged air injection and seen the fabulous results of robust performance of the system, this was particularly evident when running small systems – 5 kg/hr class. In the classical closed top design, despite the fact that there was a throat, the gas quality depended too strongly on the moisture in the biomass as well as its size. The open top re-burn design eliminated it nearly completely. In fact, even at higher moisture fraction, the performance was reliable and robust steady gasification process as observed from the flames in the burner.

The systems rebuilt this way with a cylindrical water scrubber and a sand bed filter was tested with 5 hp diesel engine with a generator that could be loaded electrically or with a water pump. The tests showed a remarkable result – that the diesel replacement was as high as 92% at full load (5 hp). This was connected with the excellent gas quality and the excess-air-at-full-load design of the diesel engine that allowed more gas to be drawn in.

Now back to human part of the story. The meeting was scheduled at IISc in June 1986. The presentations were scheduled at the hallowed faculty hall. There were demonstrations held at the laboratory. Four gasifiers were setup; one was connected to an engine–alternator to demonstrate high diesel replacement. One was running on corn-cob. One was running on fuel-pellets.

The demonstration was a run-away success. Prof. P. P. Parikh was requested to take measurements on diesel replacement and confirm the results. Dr. Vasudevan of BHEL, Trichy took measurements of various components with an anxious request for doing so. I indicated to him that if the system was deployed in the field, anybody could disassemble the system and make measurements and so how did it matter if he made measurement at this time. He enquired how we thought the intellectual property was protected. I stated that there are several features of the design that would show up in the operation of the system and hence getting the dimensions and building a similar would not help copying the product! (This feature got proved much-much later when one of the licensees before he became a licensee built a system that was similar and yet was unsuccessful in operating the system properly).

This confidence building measure was, I believe, the key to launching the thousand gasifier programme. There were other manufacturers of gasification systems in the country. Dr. B.C. Jain earlier of M/s Jyothis Limited who had formed a new company called "Ankur Scientific Technologies Ltd. (ASCENT)" at Baroda in Gujarat. He was building closed top gasifier designs following on his earlier experience at M/s Jyothis Limited. Mr. Satyanarayana, a post graduate from the mechanical engineering department of Indian Institute of Science had established a company called Associate Engineering Works Limited (AEW) at Tanaku, Andhra Pradesh.

In this period 1987-1989, many interesting developments got initiated. Dr. K.K. Singh always wanting something very visible did not find IISc wanting in taking up these challenges. He challenged IISc to take up a 100 kWe gasification project to be developed and deployed in Chattam Island at Port Blair in A&N Islands. He suggested that MNES would provide the necessary funds to set up power plants on the islands. As a demo plant a 100 kWe plant would be set up to generate electricity from the waste biomass of the major timber processing unit on the Chattam island and supply it to the workshop associated with the timber factory.

Dr. Vasudevan was to examine the possibility of fluid bed gasifier from sawdust, another waste from the Chattham Saw mills. Curiously this project that ran over the next two years did not meet with their intent and Dr. Vasudevan decided that the system would not work and returned the R&D money. This is perhaps the only one project that I am aware that has truly "failed" and the investigators have acknowledged as such.

During the early period several meetings called PICOP and conferences took place. These used to provide opportunities for the seniors to air views and present the knowledge gained in an informal way. Young people had a field day; they could see the seniors at close quarters and draw conclusion about their "knowledge". Dr. K.K. Singh always was provocative and held people to their assertions. This led to conflicts and heated arguments.

By the end of 1990, the entire gasification system and dual-fuel based power package had been installed and commissioned at Chattam island (Port Blair). What remains clear in my memory after the commissioning period is the fact that the system was delivering 30-50 kWe load, the load increasing by 30-40 % in as short a duration as a third of a second - this was happening due to welding machines being operated at the workshop. The inertia of the power generation system was such that it would not even notice this change and the operation of the system even at high diesel replacement was very smooth. One of the more satisfying features was that the DR (diesel replacement) was as high as 85-87% at load of 50 kWe and the operations of the system were indeed smooth. When these were demonstrated to the MNES team and Mr. Srivastava stayed at computer screen for more than several hours to just check out the reliability of the operations, one would expect to think that they were zapped by the performance.

I think they were impressed, but zapped, No! It also requires a minimum culture to appreciate novelty at its best. Only some of us who had contributed to putting the system together were truly zapped! We had never seen such a beautifully tuned system functioning at such a high diesel replacement and that with a data acquisition on a computer and in 1990 in an island!

Systematic developments were being continued through the nineties. Even as these developments were going on, discussions at MNES were veering around gasification systems for agricultural residues so that the typical political slogan "firewood based gasification systems" might imply denudation of forests should not hurt a government. They would like to be seen supporting agro-residue based systems as more legitimate alternative for "firewood" gasifiers. A proposal was being formulated from 1989 at IISc on this subject. The idea was to dry, and pulverize light and fine agro-residues into shapes that make them indistinguishable from each other and use them in a cyclone based gasification system to generate producer gas. This unique project was supported by MNES in three phases at a total outlay of about Rs. 1.2 crore between 1991 and 1997.

Some time in mid nineties, Dr. T B Reed visited the IISc and spent three days. Several colleagues amongst us and Dr. Reed spent most of the working hours talking gasification. Several of us also visited him at his home at Golden, Colarado in 1998.

Several new concepts were tried during this period. While small and large systems were built and tried at the laboratory, it was clear the robustness of the system was nowhere near the solid fuel based downdraft gasification system. Fuels that were tried were sawdust, pulverized rice husk, and pulverized skin of the mango seed. The system had a cyclone that had a ceramic inner wall into which the fuel powder was pumped along with air through a blower. The fuel feed rate was to be controlled to maintain the air-to-fuel ratio. This arrangement meant that one needed to control both air and fuel feed rates independently. In the case of solid fuel system, what was done was to draw-off the gas at higher or lower flow rate and the fuel bed adjusted itself to this demand by maintaining a specific air-to-fuel ratio meant for gasification.

While experiments were continuing with gasification systems being improved element-by-element, testing out ideas on gas cleaning, fuel feeding and others, the robustness of performance was always in question. Towards the end of this project, the true reasons were realized due to a combination of several experiments. It would be interesting to understand these. At this time, I had gone to a conference on biomass at Banff in Canada, talked to some scientists on other forms of biomass conversion. A subject that was being vigorously pursued was liquid fuels from biomass. I used this occasion to connect up the mechanics of fast pyrolysis to the operation of cyclone gasifiers and perhaps the impossibility of matching the performance of solid bioresidue gasifiers in terms of robustness of performance; this is how the idea of briquetting bioresidues for use in the open top down-draft system took birth.

Many important developments took place beyond this period. Major projects from MNES helped make developments and ensure that these are protected and transferred for to several industries in India for commercialization. These have been supported by several administrators at the working level – Messers K K Singh, Ajit Gupta, N. P. Singh, A K Dhussa, S P Singh, Gangesh Upadhyaya, G R Meshram, D. R. Khare, V. K. Jain and others.

Dr. C. L. Gupta, Solar energy center, Pondicherry held an important and leading position as the chairman of the project clearance committee and other technical discussion meetings through the nineties when three conferences were held at IIT Mumbai, Surat and Mysore. He was instrumental in managing a technical group with diverse and strong views on technical and program design aspects. Prof. A Ramachandran, and Dr. V. S. Ramamurthy both former and the-then Secretaries of the Department of Sccience and Technology chaired the project review meetings of the major project, Strategic development of bioenergy and lent technical authority to the review meetings.

Index