Gasifiers and combustors for biomass – technology and field studies

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This paper deals with biomass-based energy devices developed in recent times. The need for this renewable energy for use in developing countries is first highlighted. Classification of biomass in terms of woody and powdery (pulverized) follows, along with comparison of its energetics with fossil fuels. The technologies involved, namely gasifier-combustor, gasifier-engine-alternator combinations, for generation of heat and electricity, are discussed for both woody biomass and powdery biomass in some detail. The importance of biomass to obtain high-grade heat through the use of pulverized biomass in cyclone combustors is emphasized. The technoeconomics is discussed to indicate the viability of these devices in the current world situation. The application packages where the devices will fit in and the circumstances favourable for their seeding are brought out. It is inferred that the important limitation for the use of biomass-based technologies stems from the lack of recognition of their true potential.

1. Introduction

Biomass as an energy source has been known for a long time. Its use has been largely concerned with meeting demands of heat for cookstoves in domestic applications and combustors in industrial applications (Kristoferson and Bokalkers, 1986). Wood shavings in fine form from wood process industries and agricultural wastes have also been used to augment the supply of heat both in domestic and industrial situations. Sawdust has been used in bath-water stoves and industrial furnaces on grate without serious concern for end-use efficiency.

The use of biomass for electricity generation is not as widespread and attempts to meet the technology needs in this direction have not been numerous. Technologies developed towards these during World War II have been marginally modified or improved at various places during dissemination without serious attempts at proper design of the reactor (Anon., 1985).

Such a situation has arisen because the Western world where such developments had taken place earlier is now well placed to obtain petroleum resources at socially acceptable costs without having to be concerned with energy from biomass. It is only in the last decade that the problems of indiscriminate net generation of carbon dioxide are beginning to be recognized and addressed in relation to global warming. Even so, the fact that the solution lies in growing biomass, making a link with energy needs in a sustainable way, has been overlooked in favour of alternative sources of energy like solar photovoltaics.

The utility of biomass is wide-ranging – timber for construction, toys, and other high-value products in the case of woody biomass, and fodder, construction material, other utility articles, and value-added products obtained by chemical conversion processes in the case of powdery biomass. It is legitimate and appropriate to use biomass for production of value-added products whenever possible. When such a use is not possible, biomass can be used for power generation – electrical or thermal – either by direct combustion or by gasification.

This paper describes: (i) the countries where a campaign of biomass use in a sustainable way is likely to succeed; (ii) the recently developed biomass conversion technologies along with their performance; (iii) environmental and safety aspects; and (iv) possible application packages.

The paper does not discuss wood- and powdery-biomass-based stoves for domestic and large-scale cooking requirements, as these have been discussed elsewhere (Mukunda et al.,1988; Mukunda et al., 1988a).

2. Possible avenues for the success of biomass energy

Economic considerations are the strongest motivators for the choice of any technology, including biomass-based

systems. Though other factors such as CO_2 concentration build-up in the atmosphere and the consequent global warming problem are matters of great concern today, simple economic considerations are the best argument in favour of any technology including one based on biomass. One clear strategy would be to identify countries, and sections within them, where biomass-based technologies can provide substantially superior and economically viable alternative energy services.

It is also necessary to consider situations where biomass-based technologies are unlikely to succeed for a long time. Countries rich in oil/gas would not look for an energy source in biomass-based fuels unless the environmental degradation costs are taken into account. While this aspect is being debated amongst technologists and policy-makers, the day when such an accounting takes place is still far off. Next, those countries which derive energy from coal-based power stations will continue to do so in view of the availability of the fuel and the enormous power levels (200 to 500 MW) at which such power stations are being operated at present.

In planning a large-scale power station based on biomass, two factors must be taken into account. The biomass must be harvested from a large enough energy plantation, natural or cultivated, and prepared before use in the energy devices. This occupies a primary part of the technology. In sugar industries, the availability of captive bagasse or trash from sugarcane leaves makes it feasible to have medium-sized power stations, with cogeneration, at power levels up to 50 MW. The second aspect is the size of the community which is to be serviced. If a country has a number of large cities/towns, the demand power level is high, and here again, the questions of biomass availability, procurement, and processing pose problems that may need to be solved only if there is a significant national urge to do so. By and large in such situations, oil/coal-based technologies developed in advanced countries are deployed.

We can now ask where biomass-based technologies are likely to succeed. The countries that need to import oil/coal for energy, have their population scattered in a large number of remote hamlets/villages so that grid power is expensive, and islands far removed from the mainland with few sources other than biomass are all good candidates for energy exploitation from biomass resources. Some countries which belong to these categories are listed in Table 1 along with the relevant details. It can be seen that the rural population constitutes upwards of 60% in most of the countries considered. Most developing countries are densely populated (in terms of population/available area), India ranking highest in this regard. The energy/capita, considered as an index of the quality of life, is low for most developing countries in comparison to the world average – 3 to 15%. The oil consumption per capita is hence not large compared to the world average because oil imports are a heavy burden on the economy. Since oil is in short supply, industrial activity and transportation which depend on oil resources for energy are inhibited. Brazil stands in contrast to the others in

Table 1. World scenario on energy utilization

Country	Area $10^3 km^2$	Popln $\times 10^6$	Popln density (/km²)	% ge of rural popln	Energy /capita GJ	Oil import 10^3 tonnes	Oil use /capita (kg)
Ghana	230	14.9	64.8	67	3	1015	67
Kenya	570	24.2	42.4	77	3	2178	91
Senegal	193	7.4	38.3	62	4	780	106
Tanzania	886	24.5	27.6	69	1	557	20
Zambia	74.3	8.1	109.0	45	6	540	64
India	2973	849.5	285.7	72	9	20793	61
Philippines	298	61.5	206.4	58	9	11372	184
Brazil	8457	150.4	17.8	28	22	28617	301
Cuba	-	-	-	-	23	7686	-
World	130099	5267.8	40.4	57	57		565

several ways – the population per unit area is small, the rural population is a small fraction of the total, it has its own petroleum resources (not shown in Table 1), but also imports large quantities. For this last reason, it needs to look for alternative sources of energy.

It may be appropriate to ask what the impediments to the use of biomass-based devices in developing and developed countries are. In most countries, biomass has been the source of energy – largely for heat – for several thousand years. In the last hundred years, both oil and coal have replaced biomass in a significant measure in all developed countries. Since the role model for development in most developing countries comes from the developed, similar changes are being directed by governmental actions wherever possible. One of the reasons lies in the availability of combustion devices for application to industries. An industrialist in a developing country can easily order a natural gas burner or an oil burner and associated fitments to a boiler, a melting equipment, or a furnace and have it serviced much more easily in comparison to what may be expected from biomass-based devices. Another reason lies in an exaggerated projection of other alternative/renewable energy devices. The degree of importance given to wind energy, solar photovoltaics, and, to some degree, microhydel systems simply overshadows the biomass energy so much so that most educated people including industrialists rarely count biomass energy as a feasible alternative energy source – the cheapest of the alternatives and renewable, and benign in terms of environment. While for the developed countries such a situation means little now, and also for a few decades to come perhaps, developing countries attempting to follow in the footsteps of the developed countries are being grossly misled from economic considerations.

The reasons advocated in this article for the choice of biomass energy for developing countries are different from those for developed countries.

Developing countries that import oil and have a sizable population residing in scattered villages and hamlets can benefit substantially from the use of biomass gasifier-based internal combustion engines coupled with alternators for the generation of electricity at power levels of 5-100 kW at installation costs about a third of those for

a microhydel system, a quarter of those for a wind energy system and a tenth of those for a solar photovoltaic system.

Encouraging the use of biomass in a sustainable way is perhaps the most benign way of energy extraction in an environment friendly way.

Developed countries rich in biomass resources generally, also burn up oil and coal in large quantities, releasing enormous amounts of CO_2 into the atmosphere, causing the greenhouse effect and consequent global warming. As compensation for this, biomass must be grown and energy extracted to partly replace oil/coal used for such purposes. Hence the motivation for the use of CO_2-neutral technologies from global considerations becomes the compelling reason for the choice of biomass. In addition to the use of biomass for electricity generation through the gasification route, it can also be used for generating high-grade heat, as will be shown later in this article. Also, the use of low-NO_x combustors for space heating applications has yet to be tapped. The possibility of using low NO_x through pulverized biomass cyclone combustors at low excess oxygen ratios and/or gasifiers with special staged combustors remains to be explored.

3. Biomass classification and properties

Biomass can be classified into woody and powdery, based on its availability in the natural form. The former connotes biomass whose average density is greater than about 200 kg/m^3 and ash content limited to about 2%. Typical examples are firewood, cotton stalk, mulberry stalk, corn cob, coconut shell and other similar materials. Woody biomass is not limited to firewood; several agricultural wastes also qualify for this title. All other biomass which is in loose form and of lower density is identified here as powdery. This includes several or most agricultural residues like rice husk, rice straw, bagasse, sugarcane trash, groundnut shell, coir pith, prunes from tea/coffee plantations and so on.

The reason for the choice of the term powdery is that many agricultural wastes are close to a form in which pulverization with a low-power device (0.05-0.1 kWh/kg) can bring it into the form of powder. This also increases the bulk density of the raw material, helping in transporting it at lower cost. Once the biomass is pulverized, the energy conversion device may be designed to accept a variety of biomass. The density of such biomass is in the range 50-150 kg/m^3 and ash content up to 20%.

It is known that all biomass has roughly the same CHNO composition on an ash-free basis (Kaupp, 1984). The calorific value (energy content/kg of fuel) of all biomass is also about the same excepting for variation due to the effect of non-combustible mineral content.

In sun-dried condition (moisture content of 8-10%) the calorific value of all biomass is in the range of 12-16 MJ/kg. At the lower end of the range are rice husk and straw and at the higher end wood, bagasse and such materials. The calorific value of coal found in India and a few other parts of the world having high ash content of 30-40% is about 15-20 MJ/kg, and biomass is comparable in heating value to such coals. While coals have to be mined and transported over long distances for use, causing economic problems on the one hand and global warming effects on the other, biomass can be grown in most places except where the use of land and water for biomass production is not possible

4. Woody biomass gasifier

4.1. Reactor

The principal element of a woody biomass gasifier is the reactor. This is where the wood chips loaded into the gasifier and the air drawn in react to generate combustible gas. Reactors built in Europe during the forties are of a closed-top design which has been maintained by several manufacturers even till recent times. These reactors have a large conical container for storing wood chips inside, and towards the bottom are air nozzles through which air is drawn into a restricted zone where combustion takes place. Downstream of this zone is a throat through which all the gases and the char pass. The gases then pass through a packed bed of hot char and the principal reduction reactions take place in this zone. The inherent problems related to this are discussed in Mukunda et al. (1993). In contrast to this design, an open-top configuration based on a laboratory model of Reed and Markson (1982) was evolved at the Indian Institute of Science, essentially to overcome the unreliable operation of the closed-top design, particularly when the feedstock has high moisture content (around 25% or more) and also to provide a good turn-down ratio with low tar content (Mukunda et al., 1993). The reasons for the good performance of this design *vis-a-vis* the closed-top design have been adequately addressed in a recent paper (Mukunda et al., 1993) and will not be detailed here. Stated briefly, the improvement in performance is related to the more homogeneous flow of air through the bed which is near one-dimensional, and to the fact that the approach to a final fuel-rich condition is from an initial lean state through stoichiometry. The second point leads to lower generation of tar, and whatever is generated is cracked to smaller-sized molecules as the gas traverses a long uniformly-arranged bed of hot charcoal without any low temperature zones.

The current design of the reactor consists of a vertical tubular reactor with an open top and a water seal at the bottom. The lower two-thirds of the reactor, where the reactor bed temperature exceeds 600°C, is lined with a ceramic material of low thermal conductivity. This zone extends from about 0.75m above the air nozzle to the reactor bottom. This prevents high temperature corrosion because of the presence of CO_2, O_2, CO, and carbon in the reactor. The upper part of the reactor is made of stainless steel with an annular jacket around it. The hot combustible gases generated are drawn below the grate and taken through an insulated pipe and through the upper annulus of the reactor, where part of the sensible heat of the gas is transferred to the cold wood chips inside the reactor. The entire reactor surface along with the recirculating duct which connects the bottom of the reactor to

the annular region at the top is insulated with alumino-silicate blankets. The hot gas, which enters the annulus around 500°C, transfers some heat to the wood chips inside, improving the thermal efficiency of the system, in addition to drying the wood chips in this zone. The design of the reactor is shown in Figure 1. The inner wall temperature exceeds 350°C after a few hours of operation at full power and this condition is favourable for the preparation of wood chips before their entry into the combustion zone.

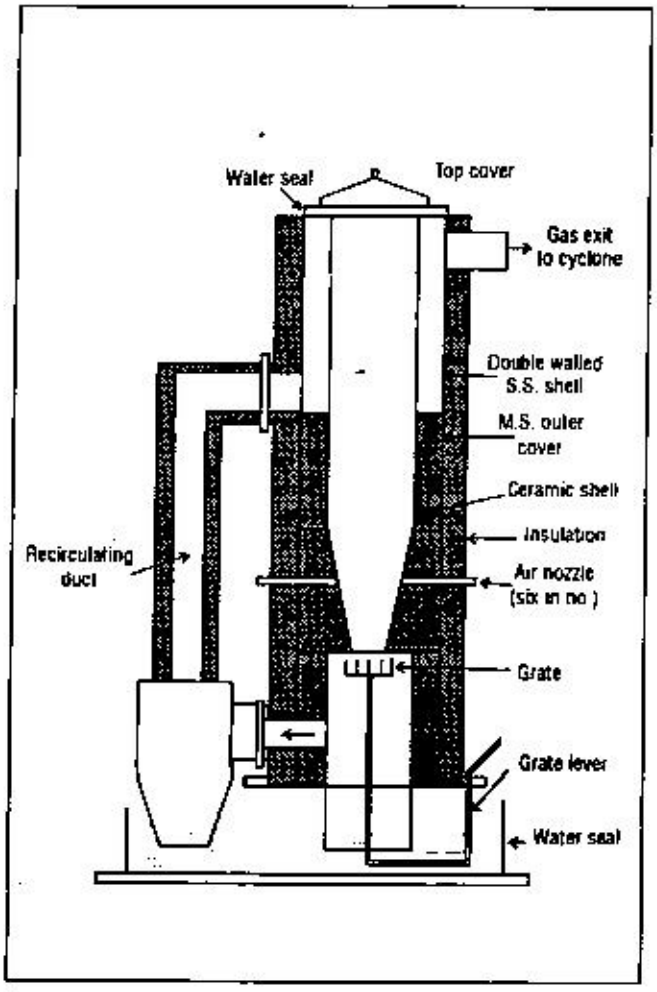

Fig. 1. Schematic of the present open top reactor. Note the flow of hot gases into the annular space of the twin shell. The bottom portion is made of ceramic material to enable extended life in the high heat zone.

4.2. System configuration for thermal applications

The gasifier for thermal applications has a hot gas clean-up system along with a method of drawing the gas from the reactor and pumping it into the utility where heat has to be transferred. Figure 2 shows the schematic of various modes of use in a thermal system. The gas from the reactor is taken through a coarse filter in order to eliminate particulate matter of large particle diameter from the hot gas. The temperature of the gas comes down significantly during this process from about 250-300°C to 150-200°C. Three different arrangements for drawing the gas along with the burner are shown in Fig. 2.

1. The gas is sucked using a high temperature blower which can tolerate some fine dust (10- to 50-micron size) and sent to the burner directly. This arrangement is useful in retrofitting on some existing burners. The air required for combustion is taken from the atmosphere and the combustion is in the diffusion mode. This is not the best arrangement for getting high combustion efficiency in the burner, but the burner can be modified to suit the site conditions.
2. This arrangement consists of an integral burner and gas pumping system. The gas is sucked from the gasifier using an ejector with air as the driving fluid and the end of the diffuser of the ejector forms the burner (Dasappa et al., 1993). The advantage of this system is that the blower will not experience high temperature dusty hot gases and handles only dry air. It has the disadvantage that the blower needs to develop high pressure and consequently to be of high power.
3. The third arrangement is a combination of the above two, with the blower directly pumping the gas and the ejector used for drawing air. It is possible to use a relatively low-pressure blower (500 mm water gauge) since the amount of work done by the ejector is small. The difference between this arrangement and the first is that air is premixed with the fuel gas before combustion. This difference leads to improved thermodynamic performance of the combustion system.

With this burner, it is possible to obtain a temperature of up to 1250°C, and combustion is intense and takes place within a short distance. It is suitable for applications where high temperatures are required, such as in ceramic industries. The overall hot gas conversion efficiency in high-power systems will be as much as 85%.

Premixing the gases before combustion gives rise to a very compact flame and flame temperatures (in an environment of thermal sink) of 1250°C or so. The overall hot gas conversion efficiency in high-power systems will be as much as 85%.

4.3. System configuration for engine applications

For engine application, gas must be cooled to room temperature and must be much cleaner compared to that for thermal applications. The cleanliness requirements are in terms of particulate and tar content. The acceptable upper limit of particulate content appears to be around 50mg/m^3 (Kaupp, 1984; Stassen, 1993) irrespective of particle size, which is generally less than 10 μm. However, if the particle size is smaller than about one micron, this limit is unimportant as the particulate matter flows along with the gas without deposition during its way to the engine at bends, corners and passages. As regards tar, there has been no clear statement of what the limit is. Understandably, no deposition of tarry material should occur in the passages. Such an occurrence is possible if the tar has components with condensation temperature somewhat above the ambient. Most updraft gasifiers produce "smelly" tar, implying the presence of components of a wide range of molecular weights including relatively low molecular weight, and this material will condense at near-ambient temperatures and will be highly viscous. Downdraft closed-top gasifiers with air entry through nozzles also

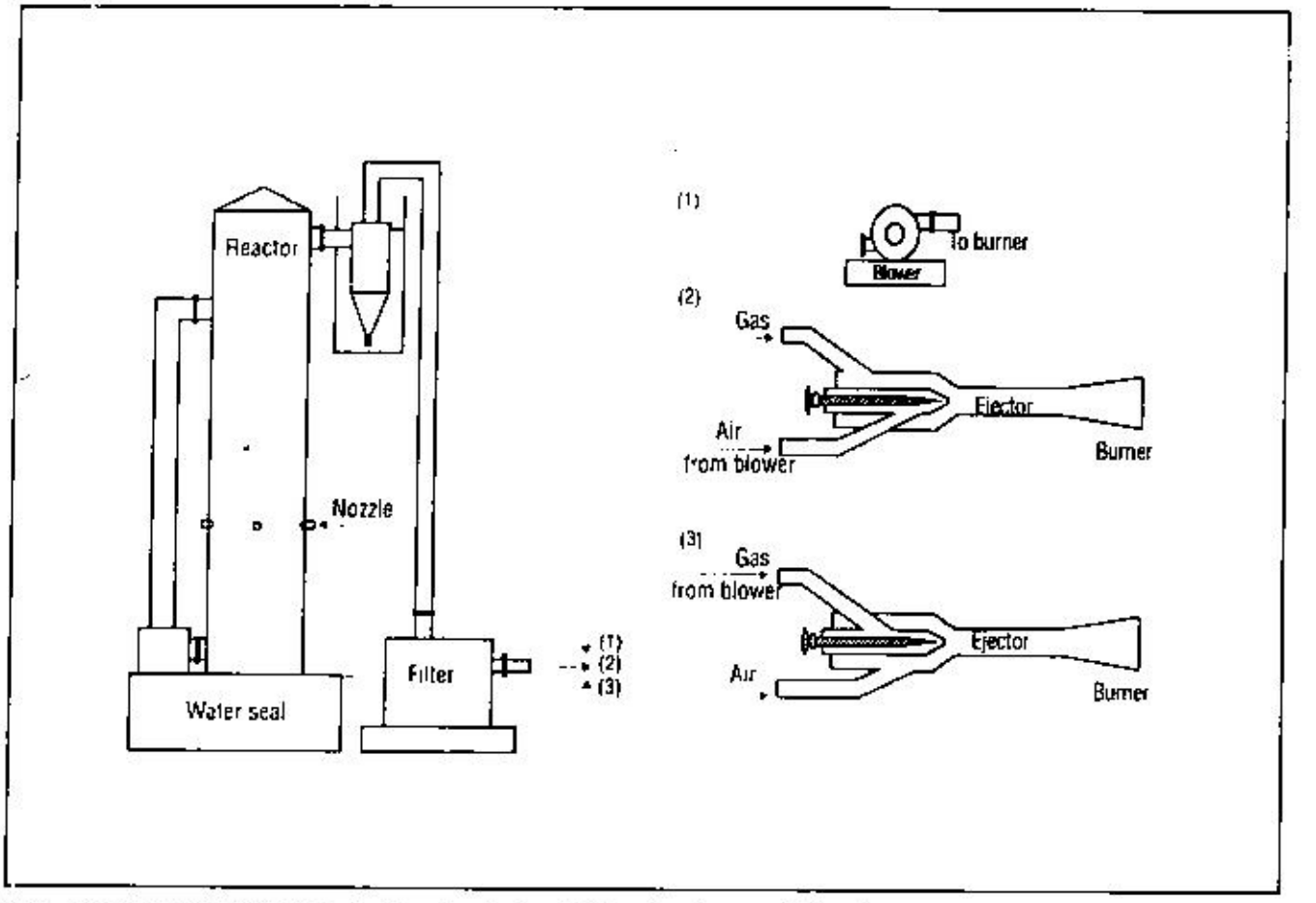

Fig. 2. Schematic of the overall system for thermal applications: 1) Blower-based system, 2) Ejector-based system, 3) Combination of 1 and 2.

permit leakage paths in azimuthal zones between nozzles for relatively uncooked volatiles and this leads to the generation of tar of a kind which still has some low molecular weight components. Open-top downdraft gasifiers allow for a more homogeneous bed of high temperature and produce much smaller amounts of tar. While the upper limit of allowable tar may be stated at 50 mg/m^3, the real test would be to couple the gasifier to the engine, run it for a specific duration and analyze the deposits in the pipeline, both for particulates and tar. This will establish the time-between-maintenance of various components. While characterization of the gasifier alone has been completed at many places in the world (Stassen, 1993), characterization of the gasifier-engine system has been done in a limited way (Kamat et al., 1991). What seems clear from the characterization of the gasifier alone and operation on engines is that the engines can run in dual-fuel mode for roughly as long a time before any major maintenance as in diesel-alone mode.

In order to increase the density of the gas, it is cooled to ambient temperature by indirect and/or direct means and is filtered adequately to reduce the particulate content. Cooling in high-power systems is best handled by direct injection of cooling water unless there is a specific plan of utilization of the low-grade heat. Figure 3 shows a direct-injection cooling arrangement with a spray tower. A sand-bed filter is deployed to remove the particulates collected by the cooling water in the spray tower. Periodic washing of this sand-bed is adequate to keep the operation smooth. With respect to filtering a variety of techniques have been considered and some tested for a reasonable period of time. Some of these are, use of polyurethane foam, synthetic cloth, coconut coir mat in combination with others and sand bed with specific sand particle size distribution. After these studies, the sand-bed filtering technique was finally accepted as it is convenient, inexpensive, provides good filtration, and is reusable since simple washing with detergent solution is adequate to refurbish the filter. The filter is separated into coarse and fine sections. The coarse filter is filled with sand of 0.5- to 2-mm size particles and the fine sand bed filled with 0.2- to 0.6-mm size sand. The size of the filter area is so chosen that the gas velocities through the filter bed do not exceed 0.1 m/s. This low velocity coupled with the tortuous path causes the removal of a large part of the dust from the gas. Experiments have shown that some part of the tar also gets deposited in the filter circuit, particularly when the moisture carry-over from the cooler causes slight wetting of the sand bed.

4.3.1. Gasifier performance

The performance of the gasifier can be described in terms of the composition of the cold gas, its calorific value, the particulate and tar levels at various loads. The ratio of the cold gas flow rate to the wood consumption rate is about 2.6±0.1. This value is consistent with earlier experimental data quoted in an SERI document (Anon., 1979).

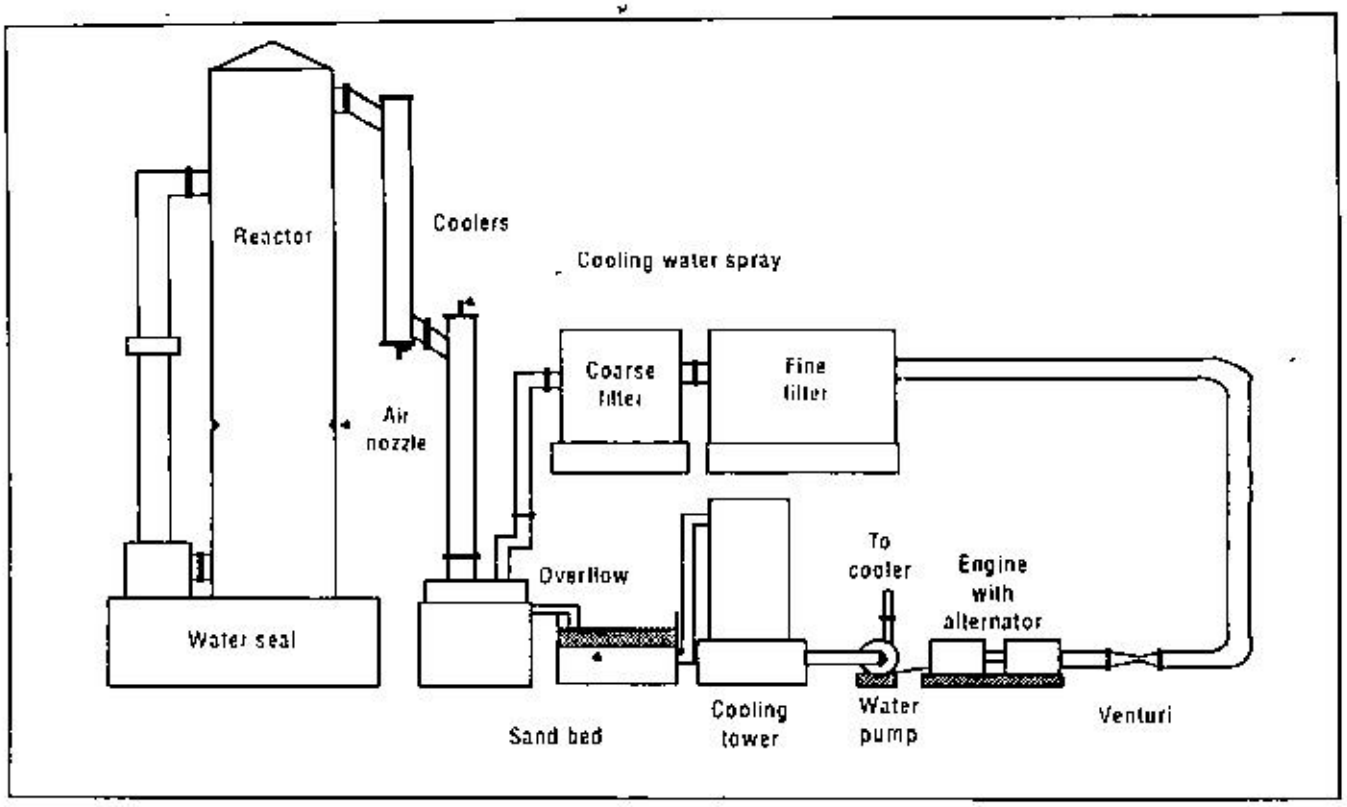

Fig 3 Schematic of the reactor-cooling and cleaning system for engine applications Notice the spray cooling tower deployed to help recirculate cold water

The gas composition and calorific value at a typical high load is provided in Table 2 as a function of the run time of the reactor. The gas composition is in the range H_2 = 18±2%, CO = 19±1%, CH_4 = 1.25±0.5%, CO_2 = 12±2%, and the rest N_2. A plot of the calorific value with run time of the reactor is shown in Figure 4. The calorific value keeps rising from 4 MJ/kg to 4.4 MJ/kg in about two hours. The particulate and tar (P&T) data are taken from a major test done for DASAG (Switzerland) in this laboratory along with some Swiss scientists. The sampling and analysis procedure for P&T was evolved by the Swiss team. The experiment included P&T data analysis for both hot and cold ends. The reason for this is as follows. The amount of P&T generated at the hot end has to be brought down to acceptable levels by the cleaning system. Should the amount at the hot end be very large, then the load on the cleaning system also will be significant. This implies the need for a more elaborate clean-up system and/or more frequent maintenance. It is not often that P&T data at the hot end is obtained, as very little is reported in the literature. The present results are shown in Figure 5 for both hot and cold ends. The results indicate that the hot-end tar is about 100 mg/m^3 and comes down to 20±10 mg/m^3 at the end of the fine filter (cold end). Part of this tar is washed by the cooling water, part is deposited in the sand-bed filter. The particulate level also comes down to 50 mg/m^3 at the cold end from about 700 mg/m^3 at the hot end.

Table 2. Gas composition (volumetric %) and calorific value for a typical run

T[a] min	CO	H_2	CH_4	cmb[b]	CO_2	N_2	H_2O[c]	Ar[d]	sum	μ	Q MJ/kg
0	15.57	17.74	1.06	0.25	13.26	50.36	2.50	0.50	102.24	25.55	3.97
59	10.44	16.51	0.69	0.25	9.95	49.23	2.50	0.50	98.07	24.22	4.16
119	18.00	17.52	1.29	0.25	11.75	43.53	2.50	0.50	95.34	23.41	4.56
200	19.39	16.84	0.64	0.25	10.97	60.55[e]	2.50	0.50	111.65	24.45	4.25
297	17.06	19.21	1.59	0.25	15.11	47.28	2.50	0.50	103.51	25.76	4.29
365	18.50	18.71	1.27	0.25	13.61	48.16	2.50	0.50	103.50	25.68	4.32
404	19.79	18.72	1.29	0.25	12.07	48.62	2.50	0.50	103.73	25.49	4.50
404	18.76	20.17	1.51	0.25	13.60	46.78	2.50	0.50	104.61	25.44	4.65

Notes

a Time elapsed after gas sampling was started

b cmb includes ethane and ethylene obtained during specific tests on gas chromatography

c A value of 2.5% of water is estimated to be present in the gas composition assuming saturation of gas with water vapour

d A value of 0.5% of argon is assumed to be present in the gas composition, estimated from composition of air

e A nominal amount of 48.5% is taken for N_2 in the calculation for μ, the molecular weight of the gas

4.3.2. Performance with diesel engines

For operation in the dual-fuel mode, the arrangements are similar to the one shown in Figure 3, with the addition of an engine into the circuit. The commercially available diesel engine needs to be modified only in the air intake region. The air intake is fitted with a manifold

into which the air and gas lines are connected. The air line is open to the atmosphere through a control valve. The engine sucks both air and gas in simultaneously and the gas-air ratio can be controlled by operating the air control valve. The mixture also passes through the final oil filter so that any possible residual particulate matter is held back, preventing possible deposition at the valve seat. The dual-fuel operation is aimed at reducing the diesel consumption at any fixed load. This function is performed by the governor fitted on the engine. The quality of the governor, classified as A or B, is determined by its ability to regulate the speed within specified limits. Class A, used on high-power engines, is better and maintains the speed to within 2%. Class B is of lower quality and maintains the speed to within 4%. Most 5-hp pumpsets use class B governors. Most engines coupled to alternators use class A governors. This governor is good enough to cut down the diesel flow in dual-fuel operation.

In an actual dual-fuel operation, the desired diesel replacement is achieved by reducing the air flow into the engine slowly by operating the air control valve. The engine draws in a specific flow rate through the air manifold. (This is about 120 g/s for the engine rated for 96 kW at 1,500 rpm and 11.1 l capacity at sea level.) As the sum of the air and gas flow rates is constant, when air flow is decreased the gas flow through the system increases. This increases the contribution of energy from the gas. Hence, the engine governor comes into operation and cuts down the diesel flow to maintain the speed. Reducing the air flow rate will reduce the diesel flow only as long as the gas-air mixture remains lean. If the mixture becomes richer, the engine stalls. One, therefore, has to avoid such conditions. The diesel replacement under conditions close to stall can be between 90 and 93%. Providing for an operational safety margin of about 5 to 6%, 85 to 87% diesel replacement can be obtained. This can be done either manually or automatically. In the case of manual operation, the air valve is manually adjusted to obtain the desired diesel replacement after manually measuring the diesel flow rate and load. The limitation of this system is that the response is slow in the case of varying loads, and optimization of diesel replacement becomes difficult. A diesel flow measurement unit has been developed based on first principles (of hot-wire anemometry) since no commercial system was available. The feature of this system design is that a very wide range of flow rates is covered, by a factor of 25 in terms of flow rates. A 100-kWe diesel alternator burns up diesel at 5 l/hr at no load and 30 l/hr at full load. At 80% diesel replacement, the diesel flow rate at no load is 0.8 l/hr. Since the measurement system should take care of the lowest (0.8 l/hr) and the highest (20 l/hr) flow rates, the range of measurement is large. The details of the system are discussed in Rajan et al. (1991). The unit has a flow indicator and in addition gives an electrical output which can be used for automatic control of the air valve to optimize diesel replacement. If the load is varying slowly, the air valve can be manually controlled using the flow indicator. If the load fluctuates fast or manual intervention

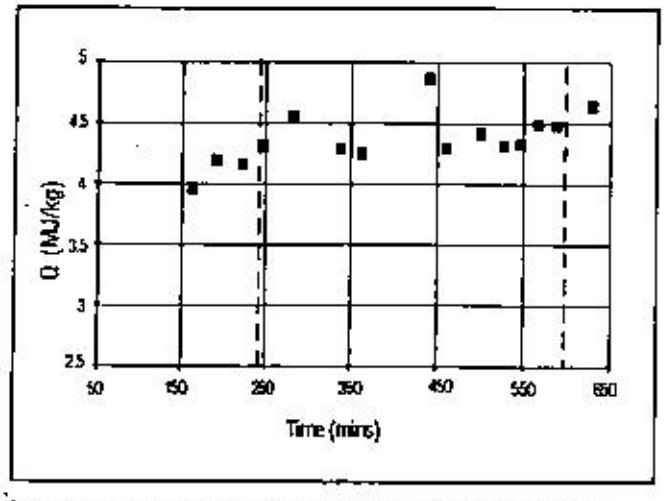

Fig. 4. Gas calorific value with time of run of the gasifier (100 kWe).

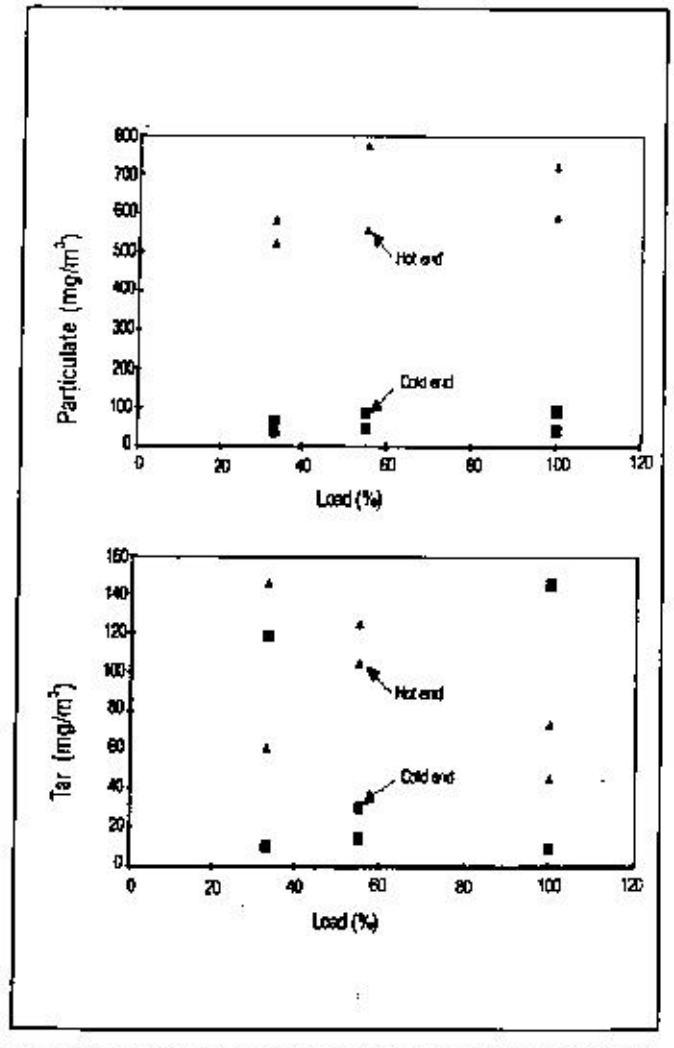

Fig. 5. Tar and particulate at the exit of the reactor and the filter at varying load conditions on a 100 kWe system.

has to be avoided, an automatic control system can be deployed. In the control system which was specially designed for use with wood gasifiers, the load and frequency measurements are also handled electronically and these are either processed in a stand-alone control system or passed on to a computer for acquisition and control. The details concerning the control system are available in Crasta et al. (1993). This system was tested in a field

installation at Port Blair and its performance found excellent.

Returning to performance in dual-fuel mode, the diesel replacement is around 85% or greater over most of the load range. The wood consumption is 0.95 to 1.4 kg/kWh. The wood consumption depends on the size of the system and the moisture content of wood chips. A 3.7 kWe engine consumes 1.2-1.4 kg/kWh and a 100 kW engine consumes 0.9-1.0 kg/kWh of wood. A moisture content change from 10% to 20% leads to an increase of 0.1-0.15 kg/kWh in wood consumption. A large proportion of moisture in wood can lead to high tar generation if it is used at the beginning of the operation when the reactor is not hot enough. The overall efficiency of operation, measured as the ratio of the final electrical energy output to the total input energy of diesel and wood, is another performance parameter. Diesel engines show full-load overall efficiency of 24% in 3.7 kWe engines and 35% in 100 kWe engines. In dual-fuel mode, overall efficiency is 21% in 3.7 kWe engines and 27% in 100 kWe engines, at 85% diesel replacement. The reduction in overall efficiency is traced to poor flame speeds of producer gas mixtures (Mishra et al., 1991).

4.3.3. Performance with SI engines

Producer gas can be burnt in gas engines in spark ignition mode. Normally, engines for spark ignition have compression ratios of 8 to 12. A study was conducted by Ramachandra (1993) to examine if the diesel engine at compression ratio of 17:1 could be modified to run on spark ignition mode. This experiment showed that the engine could run on producer gas from the gasifier of IISc design at 17% efficiency with a 25% loss in power. This finding is of considerable importance in farming applications because the demand for power for surface water pumping is not as high as the power delivered by the engine (5 hp). In many instances water cannot be pumped from open wells for longer than 3 to 4 hours because the well goes dry at the end of this duration. Hence, lowering the pumping rate does not compromise the users' need in any way. Similarly it is possible to convert high-power diesel engines into gas engines by replacing the diesel injection system with a spark plug and high-voltage generating device like the magneto as has been done by the Chinese (Anon., 1985) and Shashikantha et al. (1993) who have reduced the compression ratio to 8.5 and 12 respectively. It is also claimed by Shashikantha et al. (1993) that the overall efficiency goes up to as high as 32%, comparable to diesel engine efficiency. These developments are of importance in the new framework where engines running solely on gas are needed in applications.

5. Powdery biomass combustors

Combustion via a grate is the most common technique adopted for most solid fuels like coal/wood/rice husk. In some instances, for fine-form biomass like rice husk or groundnut shell, an inclined grate is in use. Cyclone combustors have often been described in the literature, but the discussions do not fully reveal their strength. For instance, it is indicated that their heat release rate is in the range of 0.2-1 MW/m^3 in comparison to grate combustors which have 0.05-0.3 MW/m^3 (Dolezal, 1967). Work at IISc was initiated to examine the possibility of using cyclone combustors for pulverized fuels – sawdust, coconut coir pith, rice husk, groundnut shell and any other biomass waste.

Most experiments were conducted with sawdust. The schematic of the system is shown in Figure 6. The reactor outer shell is 6 mm thick mild steel of about 1 m internal diameter and 1.2 m length. The cylindrical section and the ends are lined internally with lightweight insulation ceramic bricks. The exit of the cyclone is made of a cast ceramic block. The entry of fuel and air is at the top of the reactor. The residue at the end of the reactions (ash) is discharged at the bottom. The fuel feed system is a relatively simple one. The fuel powder is screw-fed into the entry of the suction duct of a blower (of pressure head 250 mm water gauge) which pumps the fuel-air mixture into the cyclone. Obtaining control over the air as well as fuel flow rates is a part of the design of the system. The system may be started by introducing from the bottom cap about 3-4 kg of wood logs/pieces and some rags

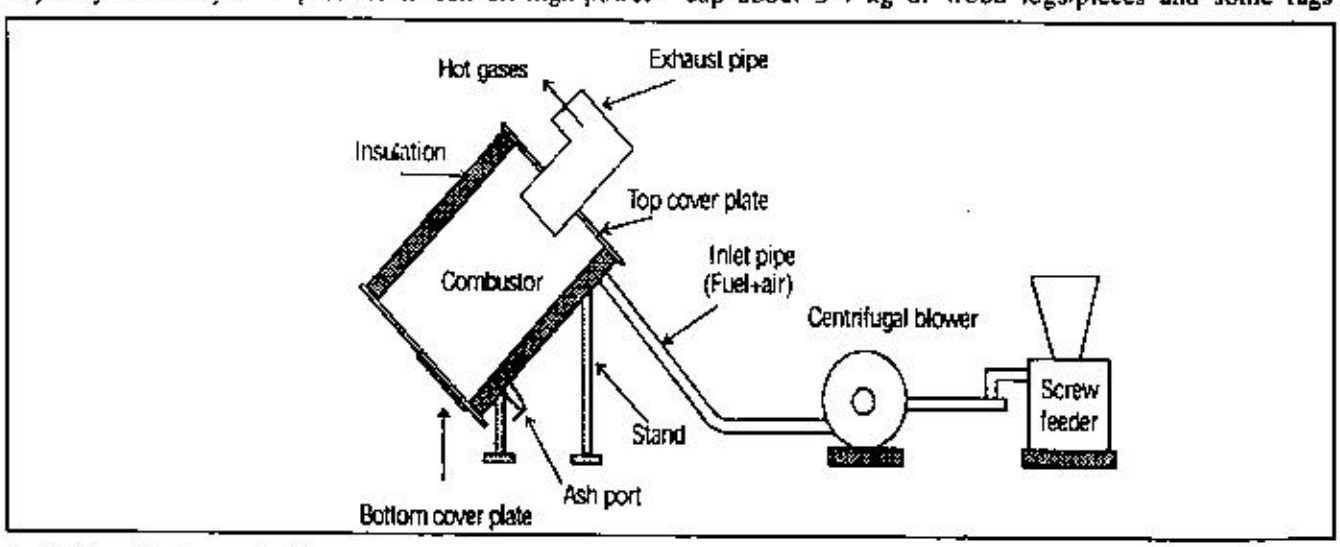

Fig. 6. Schematic of a powdery biomass combustor.

dipped in petroleum fuel, and lighting the rags. After ten minutes the air from the blower is switched on at a low flow rate along with some fuel (powder). After a few minutes, the flow rate may be gradually increased to raise the power level. At full power level, the system gives 400 kW thermal power at 3-4% oxygen in the product gas (the heat release rate amounts to 0.5 MW/m^3). The most interesting feature of the reactor is that the peak exit gas temperatures reached up to 1375-1400°C. In initial tests conducted with ceramic material rated to melt at 1350°C, it completely melted and fused. The system has been relined with material that can stand 1400°C. This feature is important in terms of the range of utility of biomass. One class of ceramic industries need a temperature of 1350°C inside the furnace for obtaining product of the right quality. They must use perforce oil-fired burners. It appears that for such cases, one can now deploy biomass-based combustors. It is important to recognise that only those combustors whose air-to-fuel ratio can be controlled accurately can reach such high temperatures. Wood combustors based on wood pieces, usually of varying sizes, cannot accomplish this, since the pyrolysis rate of the fuel is a function of the surface area and one can get widely varying air-to-fuel ratios as a consequence. This leads to temperatures which are usually lower than can be obtained with controlled and fixed optimal stoichiometry. Even so there have been cases in which ceramic industries based on wood as a fuel have achieved furnace temperatures of 1300°C at the peak. By converting the biomass to a pulverized form and using it in combustors one gets a bonus in terms of higher temperatures to enable the realization of the industrial objective without having to depend on fossil fuel. One of the further advantages with this combustor is the ability to operate at very low excess air ratios – no more than 3 to 4%. This point is relevant in the context of NO_x emission from combustors. Biomass combustion devices with grates are allowed to have much more excess air (~ 13% oxygen in exhaust) and a greater proportion of NO_x. While no measurements of NO_x from such combustors are available yet, it may be possible that one can achieve the limits (150 mg/m^3) at much less excess air.

6. Powdery biomass gasifiers

6.1. System configuration for thermal applications

The motivation for building gasifiers based on powdery biomass is to obtain combustible gas which can be piped. The gas obtained can be burnt in a combustor to achieve low NO_x by using techniques in vogue in aircraft gas turbines or other devices (Nathan et al., 1992).

Figure 7 shows the currently tried-out configuration of the gasifier. A vertical metal reactor covered with insulation (alumino-silicate) is held mechanically in such a way that under thermal load there will be no physical distortion. Tangential entry is used for air as well as the pulverized fuel. There is another tangential entry meant for start-up. In this port a high-power multi-port pulverized fuel stove of special design (Mukunda et al., 1993) is fitted, as is also shown in Figure 7. The stove provides a power of 30 to 35 kW (thermal) for 20 to 30 min. When the blower is put on the stove is lit at all the four ports. The stove begins to function at the rated power level. The hot gases from the stove enter through the tangential port and heat up the walls. After the wall temperature reaches 650-700°C, the stove is withdrawn and the port is capped and sealed.

At the end of this operation, the cover on the tangential entry carrying a mixture of pulverized fuel and air is opened and fuel is allowed to be drawn in at a low rate. This operation is conducted at flow rates near

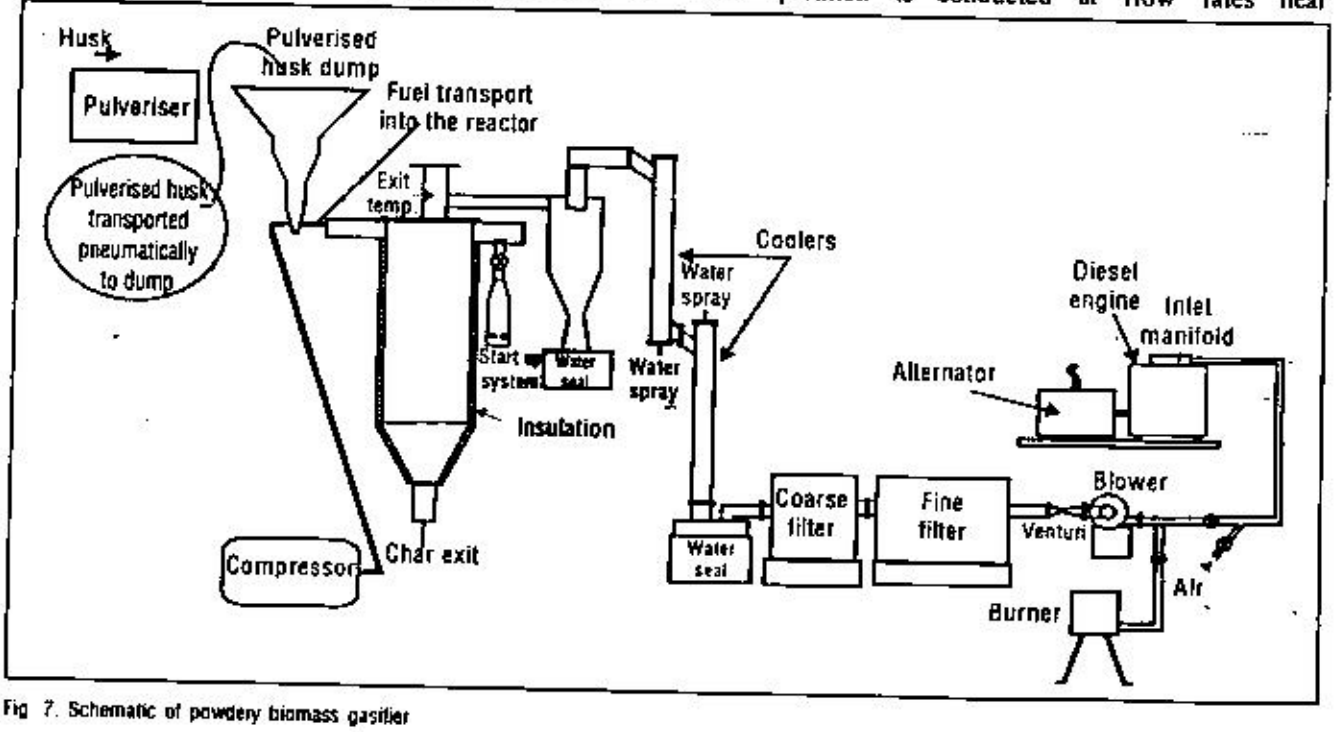

Fig. 7. Schematic of powdery biomass gasifier

stoichiometry so that the wall temperatures build up to 1000°C or so. Then onwards, the fuel flow rate is further increased slowly till combustible gas is obtained at the burner. If the fuel flow rate is further increased the air-to-fuel ratio reduces further and the gas composition may consist of more volatiles (or tar as one would expect). The band of permitted air-to-fuel ratio is relatively narrow and hence the fuel flow rate must be controlled accurately. This is in complete contrast to wood gasifiers where the wood consumption rate is not externally controlled but allowed to be determined by the system itself. (As was noted earlier, the air-to-fuel ratio for wood gasifiers is close to 1.6 : 1 and is independent of the flow rate. If we note that the stoichiometric ratio for wood is 6.5 : 1, the equivalence ratio of operation for wood gasifiers is 0.25).

To enable accurate flow rate control, a special pneumatic fuel-feeding device was developed. Based on the ejector principle, the pulverized fuel (less than ~ 2 mm size) is pumped into a pipe at air-to-fuel ratio about 2% of stoichiometric value. The flow rate depends on the geometry of the air jet, exit ducting and pressure of operation of the pneumatic source. Operated with air at 2-4 atm passing through an orifice of 2 mm diameter, the device can pump about 75-90 kg/hr of pulverized rice husk of particle size 0.25-1.5 mm.

The gas at the outlet of the reactor is at 650-700°C and is fairly dusty as the fuel fed also has fine particles. The gas first passes through a straight metal passage, when the temperature drops by 300-350°C. The gas then passes through a dry cyclone dipped in a water seal. A part of the dust is captured here; also the temperature drops by 150-200°C. At this point the gas goes through a sand-bed filter, essentially to eliminate large particle-sized dust, and then goes through a blower into a burner which draws in air by ejector action as in the case of the wood gasifier.

6.2 System configuration for engines

The system is the same as for thermal applications up to the point at which the gas enters a sand-bed filter. The abovementioned way of filtering or cooling will be inadequate for use in engines.

The gas is taken through a two-section cooler after which the temperature is brought down to ambient conditions. It passes through a two-section filter so that the exit gas is clean to the same standard as obtained with wood gasifiers. The cleaning train has to be more elaborate here since the dust content in the feed is much higher. The calorific value of the gas has been measured at values comparable to that in wood gasifiers. Tests on engine operation have not yet been completed at the time of this writing.

7. Techno-economics of the system

Most of the technologies discussed above are ready for market utilization; on some, technology has been transferred to more than one industry and intense marketing efforts are currently going on in India. It would be of interest to examine the first cost of the systems as can be made available to the market.

The cost of the woody biomass gasifier for thermal applications is as follows (these costs are 1994 prices):

30 kW: 1,000 US$; 300 kW: 9,000 US$; 500 kW: 15,000 US$.

The approximate cost of a woody biomass gasifier for electrical applications (including engine-alternator system) is as follows:

3.7 kW: 2,000 US$; 20 kW: 7,000 US$; 90 kW: 34,000 US$.

The cost for installation for thermal power is about 30 US$/kWth and for electrical power about 380 US$/kWe. These values for electrical applications are much smaller than for conventional sources – hydro, nuclear or coal-based power generation systems. Rigorous calculations of economics have been made and presented in a recent paper (Mukunda et al., 1993). The calculations indicate the cost of electrical energy to be about 0.05-0.06$/kWh. The primary parameters which control the cost of energy are the cost of biomass and petroleum fuel, the interest rates, and the numbers of hours run per year. The last factor is the most important single factor controlling the return on investment. The pay-back period works out to 2-3 years for electrical applications run between 3,000-4,000 hours per year. A rate of usage greater than this results in much better economics.

With regard to thermal applications, the economic results are more impressive. Users for whom high-grade heat is essential can obtain full return on investment in less than one to 1½ years depending on the extent of usage in excess of about 2,000 hours/year.

8. Application packages

Amongst the applications for which this technique can be used are water-pumping and electricity generation systems at various power levels. It is possible to meet the requirements of pumping more easily than for electrical energy as the problems of load following are not complex. It is possible to run a water-pumping system even with a poor diesel governor in the engine. It must also be emphasized that electric supply to an industry with 25-35% load variation can be handled by a diesel engine in a dual-fuel mode with no difficulty if the engine has a Class A governor.

The applications of the technology are for individual farmers for pumping applications, and industries and communities for thermal/electrical applications. The demand for farmers' requirements ranges from 5-hp to 50-hp pump sets, either for surface water-pumping or deep bore well pumping, at heads varying from a few metres to a few tens of metres. The requirements of tea/coffee plantations can be substantial. The total number of hours of pumping per year varies from 500-800 hours over India. This is usually during the months of December-May since the south-west monsoon sets in towards the beginning of June over most of the country.

Farmers using 5-10 hp pump sets work plots of a hectare or smaller. Those using high-power pumps are plantation-owners of a few tens to about a hundred hectares.

It is not possible for marginal farmers to buy a gasifier system as they cannot mobilize the required investment unless they are supported by the government through a subsidy. The larger farmers/plantation-owners would not

be interested in the technology as the contribution of the cost of petroleum fuels to the product cost is 6-10% unless petroleum fuels are in short supply.

The tea industry uses a considerable amount of heat energy for drying and is one prime target group for the use of biomass in an efficient way. This industry has been dependent on biomass for heat generation for over several decades, even though its practices are not efficient. For instance the use of as-received biomass of large moisture content almost directly in furnaces reduces the peak temperatures and increases the quantity of biomass per kg of tea dried. One kg of "made tea" (as it is called) brought to the condition of 3% moisture from 55-60% moisture theoretically needs 0.6 kg of sun-dried biomass of 10% moisture. The projected biomass requirement for 1 kg made tea is 1.1-3 kg. The large spread is due to various levels of carelessness including inaccuracies in weighing. There appears to be a significant possibility of reducing the biomass consumption to less than 1 kg/kg made tea and this is currently being explored. Industries which use glass melting furnaces, small ceramic tile furnaces, and potteries, can make use of biomass-based technologies.

With regard to electrical applications, the current perception is the possibility of servicing remote villages not connected to grid electricity. Sufficiently industrialized villages connected to grid electricity may also be prime targets for biomass-based electricity generation in the future because the inadequacy of power generation in relation to demand causes cut-off of supply, and invariably the village electricity supply is the victim. Realization of the effect on productivity of lack of grid supply *when needed* is growing, but the lack of an economically viable alternative has been the impediment to remedying the situation. Thus, private entrepreneurship for the generation and supply of electricity has to be exploited in the future. This aspect is important in many Third World countries, including parts of Africa, Latin America and India.

9. Field experiments and experiences

Field experiments started with the programme of the Government of India for dissemination of gasifiers. About 300 gasifiers were built over three years and disseminated to individual farmers, initially without payment, and later on payment of about 60% of the cost of the engine-pump set. Monitoring of the performance of these gasifiers showed that about 30% were used in diesel mode and 40% were not used at all. The last feature was because the process of dissemination did not take into account the site conditions properly. In several cases, the source of water for pumping dried out too soon for the farmers to use the system. During this period the authors went around monitoring the operation of the system and worked out design modifications to help make the system more user-friendly. Details of this have been described by Dasappa et al. (1989).

Two major field experiments tried out are the village electrification scheme at an unelectrified village called Hosahalli and the irrigation water supply system at another village Ungra, both near Bangalore. The experiment at Hosahalli is more than four years old and that at Ungra about a year old. In both cases, the objective was to try out an independent biomass-based electricity generation system and examine if the techno-economics would be favourable. At Hosahalli, services of lighting, drinking water supply from a deep bore well, and flour-milling have been made available. These show that the user community will begin to demand a better and greater quantum of services once they have begun to use them; it has turned out that a 3.7 kWe system is not adequate and the system is being upgraded to 20 kWe. And with this magnitude of power, it is possible to run an irrigation water supply system as well. If this is done, the possibility of self-sustained operation appears realizable. This optimism arises out of another gasifier-based power generation system for pumping deep bore well water for irrigation purposes. The current experience at Ungra, about ten kilometres from Hosahalli, suggests that farmers are willing to pay for water at a rate at which the operational expenses can be covered completely. The reason for this kind of rate being chargeable for irrigation water is the productivity of the land increasing three- to four-fold from the level realized with uncertain rain water in this semi-arid region. The clear availability of water-on-demand means better planning and use of more remunerative crops like mulberry used for the production of silk. The experience at Hosahalli, technical and techno-economic, has been summarized by Ravindranath et al. (1990) and Srinivas et al. (1992).

The experience on the 100 kWe system at Port Blair has been summarized in an earlier work (Mukunda et al., 1993) and will not be repeated here.

9.1. Safety and environment hazards

Safety from exposure to the poisonous content of the gas, namely carbon monoxide, is an issue that must be addressed. Since the entire operation is such that the pressure in the system is below ambient, air can leak into the system while the gas cannot leak out. Air leakage to points where temperatures are high may lead to burn-off of some components and, in some instances of transient operation, flame propagation at large rates. These could cause explosion. In the early developmental trials with the closed-top design, there were such experiences. In the current design, however, no problem of this nature has been experienced. Even if a flash-back of the flame were to occur, pressure would be released at one of the water seals – near the filter/cooler or the reactor – with no untoward effect other than splashing of water.

The tar and condensates are carried into the engine directly in a dry cooling system such as is used in the 3.7 kW electrical system. However, in water-pumping applications, the wet cooling causes part of the tar and dust to be drawn away by the cooling water. This water is let off into the fields and may pose an environmental hazard. Standards have been prescribed in various countries in terms of biological oxygen demand (BOD), chemical oxygen demand (COD), phenolic content in the liquid and possibly other pollutants. The regulations are more stringent for discharge into inland surface waters than for iso-

lated irrigation fields. Some of these regulations in India (which are similar to those adopted in some other countries) are shown in Table 3.

Table 3. Standards for treated industrial effluents

Feature	Tolerance limits (mg/l) into		
	inland surface waters	irrigation lands	marine coastal areas
BOD	30	100	100
COD	250		250
Phenols	1	-	5

Measurements of these quantities on the current system show BOD to be 3.5 mg/l, COD 182 mg/l and phenols 12.0 mg/l. These values seem acceptable except that for phenols. Treatment in a filter bed is probably necessary before discharge into streams as is done in the Chinese systems.

10. Final remarks

The present paper has discussed the scientific, engineering and economic aspects of biomass-based energy sources for heat and electricity. The technology elements and their novelty have been discussed in some detail. The ability of the systems to provide heat or electrical energy at high efficiencies has been brought out. The fact that pulverized biomass can provide high-grade heat at 1350°C must be emphasized at this point. This can be an important motivating factor for several non-ferrous foundries and ceramic industries to adopt the renewable energy alternative, something not being perceived as a possibility for technical reasons.

Economic considerations show that at power levels of the range considered in this paper the investment in gasifier-based (a) thermal applications will pay back in about a year or less, and (b) power generation systems will be a commercially attractive proposition provided the system utilization per year is substantial. There are many beneficial aspects not considered in the above study. For instance, a large number of users (plantations and industries) have installed diesel engine pumping or electricity generation systems in this country since the grid power supply is not reliable enough. In these cases, the investment on the gasifier system and auxiliaries is reduced. Pay-back is ensured in about two years for the larger power system if the usage is more than 3,000 hours/year. With the new technologies, administrators and planners can generate imaginative programmes for enhancing the use of biomass as a renewable energy source as a replacement for petroleum-based energy sources. ■

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