New approach to clean combustion of solid bio-fuels with varying properties

H S Mukunda,
Indian Institute of Science, Jain University and FEAST, Bangalore

Abstract

The subject of clean combustion of solid fuels like biomass and coal with varying properties – density, shape and size is important in the backdrop of a large number of efforts to produce clean domestic heat as well as acceptable and affordable combustion systems for large scale cooking and even electrical energy at tens of MWe. This article describes the evolution of a new and novel technique for the combustion of solid fuels – largely biomass, but also included is coal. In doing so, the principles involved, the trials made on a number of systems with periodic inputs from the field and the final evolution of a geometry with the broad range of fuels the system can deal with are described. Elimination of sooting (also loosely called smoke) and smoke

Introduction

Many aspects of dealing with biomass have been addressed over the last several decades. The subject of clean cooking heat has attracted the attention of many people including enthusiasts. One principal aspect that has not deserved the attention of scientists as well as decision makers (on large scale funding including international donors) relates to the nature of the fuel itself. The primary concentration was on stove designs called under improved Chula program (especially in India) that must technically allow any biomass to be used to obtain performance – minimum fuel for cooking and little emissions. Realization that wet biomass causes problems on both aspects was slow to arrive and may not have arrived even at the present time. The realization that shape and size affect the burn rate and hence the stove performance has never been factored into the design in ways that are acceptable even at this time. Thus most national and international programs on stove development and subsidized dissemination have occurred in this environment. Most documents are to be found on stove testing and very few on combustion science based stove development. The subject of stove design and development to be performed to specifications was laid out in an early paper (Mukunda, et al, 1988). Based on the experimental study and analysis they concluded that when the air flow of the right proportion was made available for combustion the efficiencies can be high and emissions correspondingly low. At this time, they also produced stove design named Swosthee using free convective air supply. While this promised moderate water boiling efficiencies (35 – 37 %) and moderate emissions of CO and particulates, it was clear that the combustion on occasion can be sooty. What could be achieved was an averaged behavior on efficiency and emissions. The fact that air supply made a difference to the performance could be actualized when computer fans of low capacity (1 liter/s at 4 to 5 mm water gauge) were available at affordable cost in the year 2000+. This led to a study of most fuels *in a packed bed* to provide the required uniform power for a typical cooking duration of an hour (as per the specifications stated in Mukunda et al, 1988). It was clear what was needed was a power of 12 - 13 g/min of sundry biomass combustion for a duration of 60 mins. This implied a mass loading of 0.75 kg biomass. Since biomass comes in a variety of densities - 300 to 550 kg/m^3, the volume required for packing the biomass appeared difficult and hence it was suggestive of the fact that densifying the biomass would add value to combustion as well as preparation and transportation of the densified biomass. This led to the solution of pellet stoves using agricultural residues that have had the greatest difficulty in use. The same stove would burn up ten times the volume of the fuel compared to firewood simply because of the density ratio and size differences which lead to burn rates much higher than rational for the design – inevitably leading to lower efficiencies, sooting of vessels and other undesirable gaseous emissions. The science, technology and outreach are described in Mukunda et al (2010). About 0.4 million stoves were sold in 2007 to 2010 period in a commercially subsidized venture by BP, India and it appeared to be scaled to larger outreach. Due to issues of agro-residue shortage – largely, bagasse and groundnut shells the prices of fuel went up from about Rs. 5 per kg to Rs. 10 per kg in two years. The affordability of the fuel came into serious question. BP, India got transformed into an Indian company, First Energy Private Limited, Pune who sought sustainable markets for the stoves and pellet fuels. They expanded into hospitality industry and supplied far more improvised and advanced solutions for cooking keeping the essential fundamental ingredients much as in the early design. Systems with power levels of 0.75 kg/h (3 kWth) to 3 and 6 kg/h (12 kWth and 24 kWth) were built and marketed with much success in several metros – Bangalore, Hyderabad, Chennai, Coimbatore, and other places. A total of 1500 tonnes per month of agro-residue pellets are being sold. The domestic market demands a fuel price pitched against liquefied petroleum gas of no more than Rs. 7 per kg at this time when the LPG prices have not increased as they normally would. Hence the stove availability and use in the domestic segment have in fact plummeted down as is evident in a more recent document by global alliance on stoves (internet, 2015).

Evolution of recent designs

Designs have evolved over the last ten years and these have been described in patents obtained at various stages (Mukunda and colleagues, 2005, 2008, 2014, 2015).

1. **The Reverse downdraft design (REDS)**

Figure 1: The reverse downdraft stove: fixed volume loaded pellet fuel (largely), gasification air supply from the bottom, combustion air from the top holes both needing a fan of 1.5 We for 3 kWth power.

Figure 1 is related to reverse downdraft gasification process based design for solid fuels, primarily intended for pellets or briquettes of high density, also showing the commercialized versions of the 0.75 kg/h system. As can be seen on the right most picture, the ceramic walled The use of high density ensures packaging of energy in smaller space consistent with expectations of performance on emissions as well. It is a fixed packed bed based design in which the use of the stove is for fixed durations only. It is a batch process based clean combustion system that uses gasification principles in completeness. Its features have been discussed in considerable detail (Mukunda et al, 2010). The design has been commercialized by FEPL, Pune and systems at power levels of 3 and 6 kg/h for the hospitality industry.

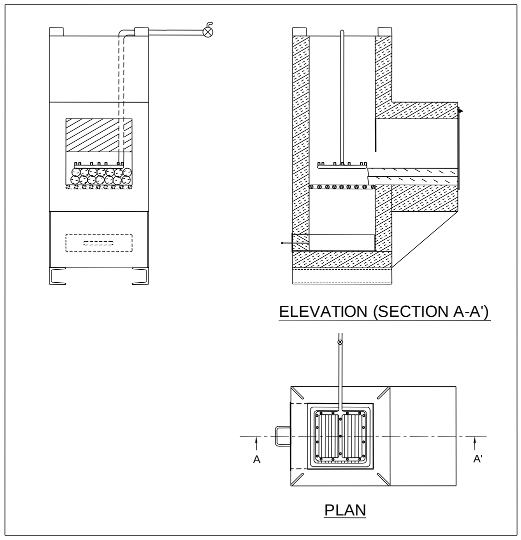

Figure 2: EIGAS system in 2005 patent

Figure 2 shows the design of a continuous stove that was described in the patent application no 1365/CHE/2005. This design uses a horizontal leg for feeding the biomass in the form of fire wood, could be other briquettes of sawdust or other agro-residues as well. This enables accessibility of the fuel feed port for introducing fuel when needed. Air was introduced in the form of fine high velocity jets (velocities of 50 to 75 m/s) at the bottom region of the vertical combustion chamber over the grate (this needed blower with power demand of 150 to 200 We). The air jets are located about 100 to 200 mm away from the fuel bed. The ejector action causes suction in the zone below the air nozzles. This enables air being drawn from the sides and the bottom region if it the bottom of the grate region is open. This air drawn through the horizontal bed of fuel through an ejector action causes a flame front to propagate through the solid fuel bed much like in a gasification system when the fuel bed is lit. This process generates combustible volatiles that burn in the vertical combustion chamber after mixing with the high speed jets of air. The hot charcoal that falls on the grate will also get converted into a combustible fuel in terms of carbon monoxide or completely oxidized to carbon dioxide or a mix of the two depending on the amount of air drawn through the bottom region. Conditions are created in the chamber for a “mild or flameless” combustion mode to dominate thereby ensuring the lowering of emissions (of CO and NO_x).

The later work as in Figure 3 is related to continuously operating system using ejector based principle. The ejector velocities are set out at 8 to 12 m/s instead of 50 to 75 m/s in the earlier design; this needs limited electric power of the order of 1.2 We for a 3 kWth cook stove. They were largely aimed at firewood even though other fuels could be used. This design continues to use a throat plate to ensure significant gasification as precursor to combustion.

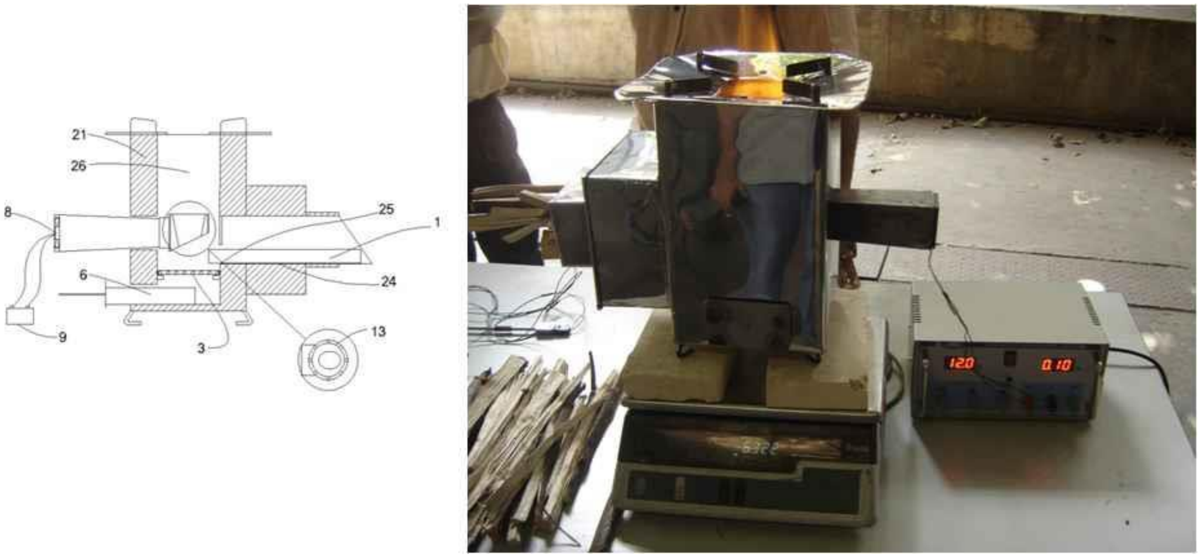

Figure 3. The EIGAS designs modified 2008 (right)

Several systems of much higher capacity were built of this design. Stoves up to 120 kg/h have been built for industrial use.

Figure 4. Stoves at 10 and 30 kg/h capacity in industrial use

At this time, there was a need for the use of a combustion device for continuously operating pellet fuel combustion system. After experimentation, it was thought that the self-feeding property of pellet fuel (8 mm dia and a length distribution of 15 to 30 mm long pieces) must be benefitted, even if the partly converted char may not move that freely on an inclined plate in comparison to the native pellet fuel. Figure 5 shows the schematics of such a stove (Mukunda et al , 2014b).

This design is aimed at combining the aspects of throat plate, bottom air as in gasification based designs (of 2005 class) and extending the design to pellet fuels of high density. These designs are also suitable for a variety of fuels like firewood and as received corncobs, broken coconut shells and similar fuels except that the extent of porosity on the fuel plate must be controlled if the performance is to be optimized. The combustion air supply in Fig. 5 indicates that the air supply is from the wall section unlike the earlier system of Mukunda et al (2014a) where the secondary air supply (combustion air supply) is in the center of the combustion chamber. This change is intended to enable better thermal protection of the air supply system that otherwise had to be soaked in high temperature flowing gases all the time.

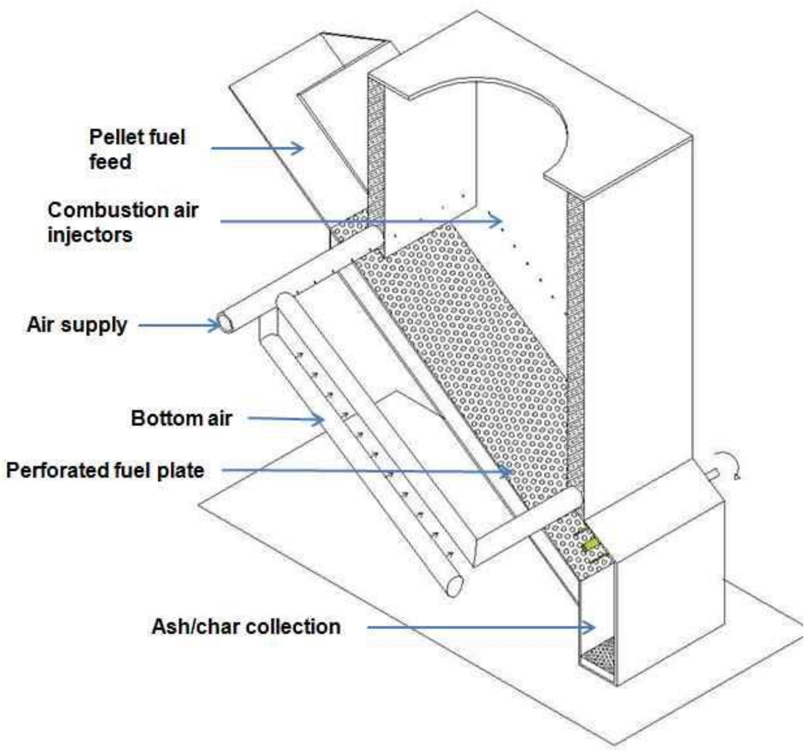

Figure 5. The enhanced hybrid ejector induced stove (E-HERS)

The bottom air was specially needed for pellets of high intrinsic density – of 1000 kg/m^3 and more, so that the conversion of chars to ash needing more time than volatile extraction in the first phase. The ejector induced combustion process is initiated in the combustion chamber with bottom air being available for char conversion. The combined effect provides a strong thermal environment for the complete combustion of the gases. Despite these good effects, there have been issues of ***sooting*** to a limited extent that is experienced because the processes of volatile generation and char conversion get mismatched with instantaneous feed rate exceeding the mean on occasions. While the solution to this problem needed careful control of feed rate near the mean value at which the conversion processes match, it was thought if ***a conceptually new design*** can resolve the problem, *so that the fuel conversion rate is what the air can induce*. Excess biomass remains in relatively cold regions so that additional volatile generation does not occur.

The most recent development is depicted in Figure 6. The crucial elements are the fuel feed zone and the air supply ducts. The cross section is filled with a specific number of air ducts depending on the power level. Each of the ducts has a specific number of air nozzles (two in the present case as can be seen in the plan view) with some space at the bottom (h_6). The combustion zone extends from the tip of the air nozzles in the zone "d" that covers a region right up to the opposite wall. At low power levels most combustion is confined to the axial distance (a_2) and at moderate and nominal power levels it extends up to ($a_2 + a_1$). Sometimes the flame may spill over the stove top. The nature of these flames is jet like issuing out of the nozzle tips with occasional switching of locations depending on the availability of the fuel vapors at specific times. The air ducts are shaped with elongated elliptical or rectangular configuration. This is to enable fuel and char passage through intervening spaces to the downstream char conversion section. When power comes down, pushing the bottom zone with a metal stick or a thin plate into the downstream section will aid the movement. As can be noted the heights of the various sections is such that the overall height is only slightly larger than the fuel feed top region. This is very special benefit of this design.

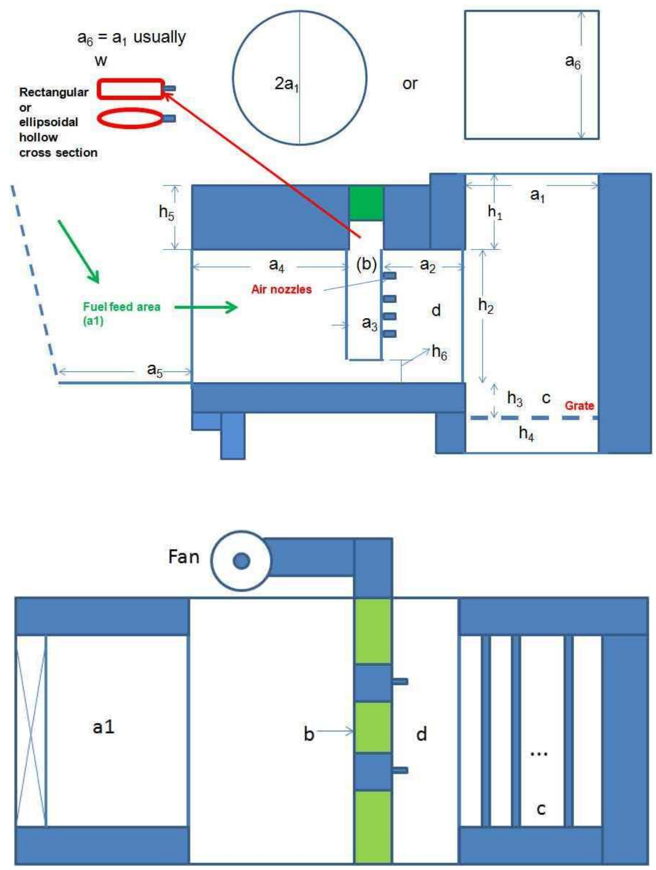

Figure 6: Schematic of the present design. The fuel feed area (a1), the air nozzles (b), the char conversion zone on the grate (c), the combustion zone (d). The air nozzles act as an interrupted throat plate.

One of the key questions that needs to be answered is: in what way is this design superior to earlier approaches in respect of the quality of combustion. This is important because designs even of larger capacity – 30 kg/h of this design behave with clean combustion with little attention paid to the fuel bed except in terms of piling up such that the entire cross section near the air entry zone is covered and an occasional movement of the bottom of the bed; it is very intriguing and compelling to explain the behavior of this simple design compared to other designs where relatively standard thought process went into conceptualizing the design – use of throat plate to ensure the gases from pyrolysis actually pass through a hot bed of charcoal.

A small piece of biomass in the bed begins to lose its contents when the surface temperature reaches 100°C at which time the absorbed moisture is released. Between 200 to 300°C, the gases issuing out of the biomass are composed of light volatiles – oxygenated components like acetic acid, furfural, and aldehydes. Between 300 to 400°C, more significant release of the volatiles occurs. This consists of a combination of levoglucosan, small fractions of CO, CO_2 and H_2. Between 300 to 400°C phenols, higher alcohols get generate largely from the lignin part of the biomass. Since there is an overlap of temperature and effusion rate of volatiles has a peak around 300 to 350°C, the only meaningful inference that can be drawn is that most volatiles are oxygenated compounds that get mixed with air drawn by suction – ejector effect and meet the air issuing as jets in the high temperature zone just downstream of the air tubes. It must be noted that at this stage there is very small fraction of unsaturated or aromatic hydrocarbons, the chance of forming soot will be nearly absent. However if the mixing with the air for combustion is delayed because the air availability for combustion is farther down in the path of the gas, an opportunity for further thermal cracking is provided for. If the intersection with air is delayed later in the flow path those segments will undergo break-up and thin soot strands result. This is *not a continuous phenomenon* and the soot formation seems to depend on the specific adjustment occurring in the packed fuel bed favoring the formation of soot; the entire phenomenon is random and hence does not allow for any possible management to eliminate it.

In view of this understanding, what has been observed in the horizontally positioned air supply system directly interacting with fuel bed somewhat serendipitously can only be explained post-facto and could not have been anticipated ab-initio. In any case, having discovered this mode of functioning, full advantage must be taken of the process robustness in the avoidance of sooting.

Variants of stove designs

Variants of the stove designs for two pan cooking operation, large scale heating for steam generation as well as frying applications are more efficiently arranged with this stove design. Because the combustion process is horizontal, two vessels can be accommodated (may also be three, if so needed) with the first vessel being set out so that there are no air flow paths from the annular region of the first pan. The second pan arrangement can be set out with any vessel – shape or size. The combustion system for large power levels can be arranged such that the ash extraction system is just below the fuel storage and gasification region. This separates the presence of char in the combustion zone. Thus this system is close to gasifier in operation. The use of porous fuel storage system allows for cross-draft gasification coupled with downdraft gasification approach as well. All these add to the cleanliness of combustion operation. Figures 7 and 8 show applications for two pan cooking and large scale heat delivery.

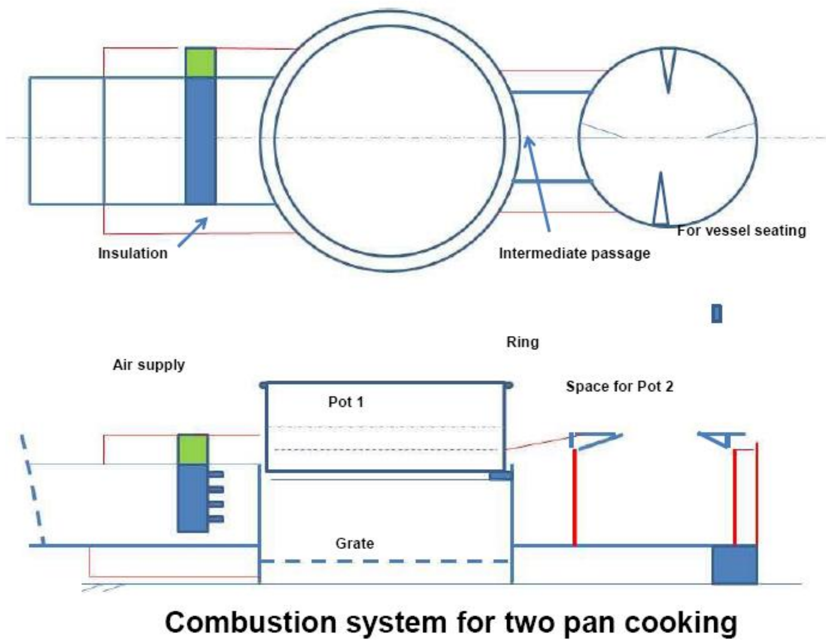

Figure 7: The fuel-feed, fan air supply, combustion zone, char oxidation zone (over the grate) and the arrangement for keeping the vessels

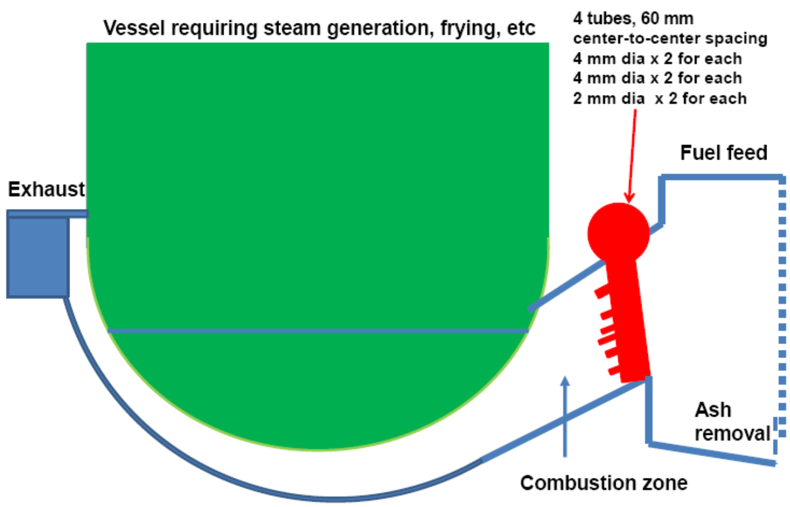

Figure 8: The arrangement for large scale combustion and heat extraction applications.

Summary

This paper is concerned with a description of the evolution of clean combustion process for biomass. Early stage of the evolution was aimed to using ejector action to draw air through a bed of bio-fuel pieces (or even long think pile of firewood packed together). The combustion process was arranged so that the volatiles could pass through a bed of charcoal facilitated with the introduction of a throat at the end of the fuel bed. The air jets were located in a combustion chamber separated from the fuel bed, typically, 100 to 200 mm away. This design was practiced with a variety of variants designated as EIGAS, HERS and EHERS for firewood, pellet, briquette and other mildly processed agro-fuels with results of high efficiency, but occasional problems of sooting. In these designs the fuel supply into the hot zone was imposed on the combustion system. The possibilities of excess fuel vapor evolution leading to zones where the fuel fragments get pyrolyzed in the high temperature zones to lead to some sooting was not eliminated. This was particularly important because a good behavior of the stove could be simulated in a laboratory condition but not observed in the field conditions since the use could not always be considered to be occurring in a regulated manner. The design designated SM-HCCD aims to overcome this problem (a) by the regulation of fuel entry into the combustion zone because of the air supply ducts acting as "interrupted throat plate". Further the combustion process of the partly premixed vapors of fuel is initiated close to the vapor generation region, albeit with premixing of air. This seems to produce excellent combustion process.

References

1. H.S. Mukunda, U. Shrinivasa, S. Dasappa, S. B. Sunil Kumar (1988), SWOSTHEE - Portable Single Pan Wood Stoves of High Efficiency for Domestic use, Sadhana, Indian Academy of Sciences, 13, pp.237-270.
2. H.S.Mukunda, S.Dasappa, P. J. Paul, N. K. S. Rajan, Mahesh Yagnaraman, D.Ravi kumar, Mukund Deogaonkar (2010) - Gasifier stoves- Science , technology and field outreach, Current Science, v. 98, 5, 627 – 638.
3. Internet (2015) ***www.indiaenvironmentportal.org.in/.../india-cookstove-and-fuels-market*** ***in*** **http://www.cleancokstove.org**
4. H. S. Mukunda, S. Dasappa, P. J. Paul and N. K. S. Rajan, (2005) Indian patent "Biomass stove" on reverse downdraft stove (commercially termed, OORJA)
5. H. S. Mukunda, S. Dasappa, P. J. Paul and N. K. S. Rajan, (2008) Indian patent "Ejector induced gasifier stove (EIGAS)"
6. H. S. Mukunda, B Dixit, and Y. Srinath, (2014a) Indian patent "Improved ejector induced gasifier stove (HERS)"
7. H. S. Mukunda, B Dixit, and Y. Srinath, (2014b) Indian patent "Enhanced hybrid ejector induced gasifier stove (E-HERS)"
8. H. S. Mukunda, (2015) Indian patent "Sized multi-fuel horizontal clean continuous combustion device (SM-HCCD)"
9. Ramakrishnan, S and Moeller, P. W., (2002) Liquid smoke: product of hardwood pyrolysis, Fuel Chemistry Division Preprints, 47(1), 366
10. Patwardhan, P. R., (2010) , "Understanding the product distribution from biomass fast pyrolysis", *Graduate Theses and Dissertations.* Paper 11767, Iowa state University, Digital Repository@ Iowa State University.