Progress in Biomass combustion and applications

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Abstract

A large part of the World in Africa, Asia and Latin America with economic levels much lower than OECD countries still depends on biomass and charcoal for domestic and larger scale cooking applications. Conversion processes of biomass to charcoal currently in use in these countries are environmentally unfriendly. Thus, clean thermal conversion of biomass to charcoal and clean combustion of biomass are the essential ingredients of the solution to deal with climate change problems. The pellet related solutions in place in Europe depend on forest sources and are expensive because the solid stock is chipped and ground into powder and then pellets are produced. It is important to address fuels in terms of agricultural residues that vary in shape, size and moisture with strategies that are affordable and make these fuels available in standardized forms to improve accessibility. Lower cost methods for obtaining pellets with lower density will be described to enlarge the basket of available, affordable and accessible solid fuels for clean combustion.

Modern strategies for clean combustion are rooted in fan based in-situ gasification using reverse down-draft stove (REDS), also called top lit updraft (TLUD) systems that can be made very efficient and clean for periods of 1 to 3 hours in a batch mode for a wide range of power levels – small to large (1 kg/h to 100 kg/h or more). However, *the new and more useful continuous combustion strategy* that adopts partial gasification is made emission friendly by adopting mildly leaner combustion again at power levels of 1 to 150 kg/h or more. The thermal extraction efficiencies with either of the approaches will improve with use of vessels of larger lateral sizes compared to the size of the combustion system in cooking solutions. The novel science involved in developing clean and high efficiency solutions will be described. The results of emissions from both batch mode and continuous combustion systems are set out in detail with focus on domestic applications . Automated and high technology (and expensive) combustion solutions from Europe as well as the relatively inexpensive and affordable solutions in practice in India for Asia and Latin America will be described. The reverse down-draft design can be converted to produce charcoal and also to burn charcoal with emissions comparable to those from clean wood burning combustion systems. Faster adoption of many of the continuous combustion technologies offer opportunities for (a) rural entreporeneuralship and many jobs with average skill to produce prepared fuels and market them and (b) mitigating climate change problems. At this time the effort is limited by the continued lack of appreciation of the *affordable advanced solutions* and approaches that involve multiple scales of use - domestic and commercial types.

Key words: Biomass combustion, New combustion devices, ejector induced combustion

Contents

List of Symbols

English Symbols

A/F	Air-to-fuel ratio
CGPL	Combustion and Gasification Laboratory
EIGAS	Ejector induced gasifier system
EU	European Union
FLF	Fuel loading flux
HC^{3}D	Horizontal continuous clean combustion device

ISO	International Standards Organization
LPG	Liquified petroleum gas
OECD	Organisation for Economic Co-operation and Development
PM	Particulate matter (mg/MJ or mg/m^3)
REDS	Reverse downdraft stove
TLUD	Top lit updraft
VEBCOD	Vertical ejector biomass combustion device
V_s	Superficial velocity, m/s

1 Introduction

Biomass is rightly credited with fulfilling the societal needs of food, fodder, fibre, chemicals and energy. Biomass waste is expected to be the source of energy or really, heat at high temperature, certainly in developing societies that depend on biomass more critically for their needs. The rich and urban communities depend more significantly on synthetic products for fuel, fibre and chemicals. Biomass as an energy source has been the mainstay of the needs of cooking in developing world over several hundred years despite its widely varying properties in terms of moisture content, shape and size all of which matter when one considers them as the source of fuel for combustion. The introduction of liquid petroleum gas (LPG) has changed the scenario for urban and rural dwellers over parts of the developing world to different extents depending on the country.

Over the last ten years, the governmental initiatives in India and China have allowed the option of LPG for cooking for a substantial number of families. Despite this, biomass cook stove as the main stay for larger cooking needs seemed and even now seems unavoidable because of perceived price differences between LPG (as measured by monthly expenditure on refills of LPG) and family-sourced solid biomass waste. Urbanization and improvement in the quality of life of rural population has demanded far more transportation vehicle dependence for goods and services. This has been accomplished with diesel driven vehicles and the cost of diesel (and of course, gasoline) has been increasing over decades with occasional dips due to geopolitical factors in a way that the national economies have had to face occasional upswings of inflation almost directly linked to the price of fossil fuels. This has led to the exploration of liquid biofuels almost always termed as bio-fuels internationally (even though solid biofuels are also biofuels!). These liquid biofuel developments that have been characterised as first generation fuels are bio-ethanol based on sugarcane largely and bio-diesel based largely on palm oil. Of course, this basket of plant oils has been enhanced over decades. Later, to enhance the contribution of solid bio-wastes to liquid bio-fuels, the second generation biofuel strategy became investigated. All the ligno-cellulosic content would qualify for conversion to liquid fuels through one of the several approaches to bio-ethanol and bio-diesel. These developments have raised questions of the relative use of biomass that includes forest residues and agricultural residues as a source of direct heat or liquid bio-fuels. The competition between direct combustion and first generation bio-fuel is with regard to land use, but for the second generation biofuel, the resource itself.

Even though biomass is so much integrated into life as a part of energy source, it figures the least in the perception and actual implementation strategy. The focus of discussions at COP26 in 2021 seemed to have had very large focus on the elimination of coal through the use of solar photovoltaics and wind as well as hydrogen as a fuel for transport and industry that the domestic needs of nearly a third of the world's population has got sidelined.

The current international focus largely on solar photovoltaic and wind energy sources, both of which serve the needs of electrical energy can at best meet the illumination and other electricity demands at homes and other establishments or grid. However, domestic or institutional cooking and other semi-industrial operations like roasting and deep frying need high grade heat which are currently based on fossil fuels, namely, diesel, liquid petroleum gas or natural gas all of which are either inaccessible or unaffordable to a large fraction of population. Hence, these applications still need alternate clean biomass based combustion solutions.

1.1 Biomass for combustion vs. liquid biofuels

A question may arise: Since liquid biofuels belong to a higher grade use of biomass, and so greater justification on the demand for biomass, whether it would influence the availability of biomass as a cooking fuel? The impact of first generation biofuels on biomass-for-heat applications is little if the land usage pattern does not get altered significantly. It is not quite so true of second generation biofuels. The key issues of second generation biofuels technologies are that they are very complex and expensive and hence, they make meaning only at large throughputs. This also implies that the annual biomass throughput has to be substantial and questions of sustainability arise. The conclusion of Zhang (2016) is that all the proposed conversion technologies remain at the laboratory, pilot, or pre-commercialization stages essentially because many questions on sustainability of the feed stock and return on investment remain elusive as far as investors are concerned. Decicco (2021) has indicated that "Total production of liquid cellulosic biofuels has recently hovered around 10 million gallons per year – a tiny fraction of the 16 billion gallons expected to be produced in 2022. Technical challenges have proved to be more daunting than proponents claimed". The major cellulosic ethanol plant by Dupont opened up in 2015 was shut down in 2017. This was bought by Germany based Verbio to produce renewable natural gas in 2018 and is being successfully operated. This will affect the availability of biomass for heat significantly. The only aspect is that sustainable operations of such facilities require establishing the chain of feed stock that itself can become a major issue.

The subject has been discussed in view of impact on climate change by Jeswani et al (2020) through a review of extensive studies on the life cycle assessment in respect of climate change and other environmental impacts. It appears that the outcome of the life cycle assessment studies are "......are highly situational and dependent on many factors, including the type of feedstock, production routes, data variations and methodological choices". Despite this, the existing evidence suggests that, if no land-use change (LUC) is involved, first-generation biofuels can—on average— have lower GHG emissions than fossil fuels, but the reductions for most feedstocks are insufficient to meet the GHG savings required by the EU Renewable Energy Directive (RED).

2 Biomass & charcoal for cooking & heating across the World

International Energy Initiative produces every year a volume called World Energy outlook and till about 2007 used to describe the role of biomass for electricity and heat in the world usage in some detail. Beyond 2008, particularly after the climate change related issues became the focus of discussions, the subject of biomass generation and use (even for heat) in OECD countries and others seem to have been overtaken by the analysis of the growth of wind and solar photovoltaics amongst the renewables.

In view of this, based on the data collated from different sources, a few profiles for countries involved in large scale use of biomass and charcoal are set out below. Whenever cooking question is discussed, most often it is domestic cooking that is concentrated upon. This is only partly appropriate. Community cooking including those at hostels, and hospitality establishments occurs at a larger scale and can be a co-promoter of ideas that include technologies and prepared biomass supply. The latter aspect is indeed very important because the cost of energy from waste biomass is much lower than from fossil fuels as is happening presently and likely to continue in future.

2.1 Europe and USA

Biomass pellets are the largest route to the usage of biomass in Europe in the USA. Mola-Yudego et al (2014) has outlined the wood pellet production at a total of 20 million tonnes including all countries in Europe. The European Pellet Council (EPC, 2021) has provided the detailed country-wise statistics. This magnitude of production of wood pellets implies the biomass harvesting would be on the scale of 50 million tonnes allowing for logging related losses.

Purohit and Chaturvedi (2011) have examined the world scenario on biomass pellets. They indicate that 22 million tonnes of pellets were produced worldwide in approximately 800 plants with individual capacity of over 10,000 tonnes. The annual growth of biomass pellet production has been close to 20 % over the last decade, and has increased dramatically in recent years, mainly due to the demand created by policies and bioenergy-use targets in Europe. The need for mitigating green house gas emissions was claimed as the important reason behind the policies in Europe.And, bioenergy was considered an important technology for combating the emissions.

Brack (2020) makes some important arguments in the backdrop of the climate change discussions - "While there is a difference between the carbon sequestration rates of individual trees and entire forests – older forests tend to contain fewer trees, as an increasing number succumb to pests or disease – studies suggest that in forests between 15 and 800 years of age, net ecosystem productivity (the net carbon balance of the forest, including soils) is usually positive.....Tree plantations are much poorer at storing carbon than are natural forests, and their regular harvesting and clearing releases stored carbon dioxide back into the atmosphere every 10 to 20 years....Sawmill residues can be used for engineered wood products, locking the carbon in the built environment, as well as for energy. If forest residues that would otherwise have been left to rot and fertilise soils in situ are removed, this may have significant negative impacts in terms of soil degradation and associated declines in levels of soil carbon and rates of tree growth..... Fast-growing energy crops, for example, are likely to be much better than wood"

The Enviva plant in the USA (Enviva, 2021) produces across ten plants nearly 6 million tonnes of biomass based pellets after harvesting nearly 20 million tonnes of trees. A substantial part of the pellets is exported to Europe.

2.2 Africa

Lambe et al (2015) have provided a succinct discussion on the assessment and way forward of domestic cook stove for sub-Saharan Africa as a proposal to the Africa progress panel. They have indicated that the production and use of solid fuels for cooking is more than 300 million tonnes and charcoal production of up to 200 million tonnes across sub-Sarahan Africa. This magnitude of use has been considered unsustainable because the rate of use is more than the production. Wood fuel in rural environment and charcoal in urban environment sustain the cooking largely. Charcoal is produced in traditional earth kilns at wood-to-charcoal conversion rates of 8 to 20 %. One of his key recommendations is that "...the charcoal sector is in urgent need of regulatory reform: Policy coherence is crucial for the emergence of a vibrant sustainable biomass energy sector, and regulatory reform is needed on both the supply and demand sides. Governments should consider removing wood fuel under-pricing policies to truly reflect the cost of sustainable charcoal production and incentivize the uptake of efficient charcoal cook stoves and charcoal production practices. Cross-subsidisation could then be used to target subsidies for charcoal to the lowest-income market segments". There are also several valuable recommendations made towards strengthening indigenous technical talent and capacity particularly because many donor contributions to the developments have not resulted in results on ground.

Santos et al (2017) have brought out that nearly half of World charcoal production came from from Africa and 35 % from South America with the total production of 50 million tonnes in 2010. Indonesia, Malaysia and China also contributed to the production of a large amount of charcoal and exported substantially to Korea, Japan and Europe. The total magnitude of the charcoal produced in 2021 across the world exceeded 70 million tonnes. Nyarko et al (2021) have set out the data for Africa: East, West, North. Middle and South Africa produced wood charcoal amounting to 32, 24, 9, 9 and 1.2 million tonnes respectively. Africa accounts for 65 % of the world charcoal production with 20 % being exported to European countries. Apparently, the charcoal industry produces great revenue, worth USD 650 million and in Kenya, has an equivalent worth of the tea sector and employs as many people as the educational sector. The essence of the argument is that the Government cannot afford to dismantle the charcoal production industry. Upgrading it will need substantive investments and a widely accepted strategy. The major recommendation of Mensah et al (2020) is the the need for integrated approaches, preferably, under "carbon-neutral charcoal" slogan. This appears to be an important consideration in the current scenario of carbon-neutral and carbon-negative approaches.

Randriamalala et al (2021) have provided a description of the approaches they chose to home on to better estimates of the amount of charcoal used in a town in Madagascar. The magnitudes provide a scale of use that is ample indication of the unsustainability of the usage.

2.3 China

Bioenergy is the domestic third-largest energy source after coal and oil, contributing to 15 % of energy consumption in 2017 (Kang et al, 2020). Their estimate of surplus biomass available for domestic use across the country is about 1000 million tonnes annually. The study is exhaustive and contains all the details of the estimation procedure. Their estimate for bioelectricity and liquid biofuels in so far as green house gas mitigation is concerned is substantial between 2020 and 2050. Both biomass-to-electricity on a large scale (via steam power plants or the more expensive gasification - gas engine based power generation) seems difficult to realize and the only way GHG can get mitigated would be via combustion systems that are far simpler to realize. Municipal solid waste in China is expected to reach 210 million tons per annum in 2020. Apparently, even these days, biomass (organic matter) is becoming a very significant energy source in China, especially in rural areas. Annually, the country produces 300 million tons of crop straw wastes, 300 million tons of forestry wastes, which are claimed to be ready for fuel production. China has had over the last twenty years, state supported industries for making large biomass stoves and produce briquetted fuel from agricultural residues as well charcoal briquettes. This effort was aimed at making domestic cooking indoor emission friendly.

2.4 Thailand and Cambodia

An examination of Papong et al (2004) and Prasertsan and Sajjakulnukit (2021) indicates that the amount of agricultural residues in Thailand is about 60 to 70 million tonnes a year. The most promising residues are rice husk, bagasse, oil palm residue and rubber wood residue. The rural segments of the country depend very significantly on bioresidues for cooking. Typically, the usage seems to be around 4 million tonnes of fuel wood, 2.5 million tonnes of charcoal, 1 million tonne of rise husk and 3 million tonnes of bagasse (the residue of sugarcane processing) constituting about 35 % of the actual residues (it must be noted that the charcoal productivity is 15 to 20 % of raw biomass).

Cambodia is in the top ten countries with the highest deforestation rate in the world, even if 57.7 % of its territory is covered by forest. A significant cause of deforestation is the production of the traditional charcoal. Papong et al (2004) provide an overview of the energy situation in Thailand with particular focus of biomass. ADB (2018) in its sectoral assessment of energy in Cambodia has set out the energy from biomass as nearly 50 % from traditional biomass such as wood, charcoal and dung. They have indicated that traditional biomass and charcoal remained the cooking fuel for nearly 80 to 85 % of the population largely confirming the consumption pattern described above. About 3.5 million tonnes of charcoal is used for cooking in households and restaurants and 0.8 million tonnes of firewood is used in the garment and brick-making industry (Sok Chan, 2019). GERES and PSE (2015) have made a socio-economic impact study on the introduction of char-briquette production and supply chain arrangement and indicate that significant value addition has occurred to the quality of life of its employees in the venture that came about due to French collaboration. Mika et al (2021) have conducted the situation analysis of energy use in Cambodia that broadly confirms the above findings.

Haruthaithanasan et al (2015) provide an elaborate outline of the biochar production in Thailand, Laos and Cambodia. The field methods used in the production of charcoal are described. They also outline the role and importance of this industry to the economy of the countries.

2.5 India

Purohit and Chaturvedi (2011) have derived the biomass surplus availability from agriculture and forestry/wasteland and have estimated them at 242 million tonnes for 2010–11, and they expect it to rise to 280 million tonnes in 2030–31 due to increased crop production and associated waste/residue availability. The surplus biomass availability from the agricultural sector alone was estimated at 123 million tonnes in 2010–11.

In India, a substantial segment of lower income families lived on a combination of traditional mud stoves and kerosene stoves. The two alternatives were perceived as essential since during continuous heavy rains or inclement weather when they do not have biomass stock and cannot look for them, they could use kerosene stoves. Beyond 2014, India focused attention on providing state supported clean cooking solutions widely. A large number of rural households (over 70 million over seven years) received free allocation of LPG cook stoves and the first LPG cylinder. The refills were to be bought by the families on their own. This approach indicated that in the first round of distribution many families did not come back for refill as they could not afford it. Over years, perhaps their economics improved and the refills were drawn after extended periods.

2.6 Important inferences

In so far as cooking food at home is concerned, somewhat universally, food cooking security demands multiple fuels because, for reasons beyond one's control, the energy for cooking may become unavailable. Biomass, kerosene and LPG *are in the order of decreasing availability, but higher perceived importance. And security has demanded* *that a wood burning stove, with some stock of biomass, kerosene stove with some stock of kerosene and* LPG *stove with one cylinder are a part of domestic inventory.*

When a survey was undertaken (in India) in 2009 - 2010 period (before the introduction of free LPG connections to deprived communities), the above facts were reinstated and further, what it showed was that there were other factors related to the usage of LPG. Firstly, there was a strong correlation between whether families had a two wheeler - a motorbike and a television set. Those who possessed these would usually had a gas connection. The cooking practices in most homes was such that if it came to boiling water, making tea (or a drink) for home or for unannounced guests (in particular), they always wished to use the gas stove for two reasons - one, for making sure that it was a quick action and second, for showing (or showing-off) that they also have a gas connection - and it was believed that possessing a gas connection would be seen as "urban" rather than rural and their self-esteem was deeply linked to it. These features seem somewhat universal because it is often times discussed in terms of development ladder. This did not mean that "wood stoves"were or are not used. They indeed are. For cooking lunch or dinner for a reasonable number of people in the family - could be four to six and additional workers around the home, it is always wood stove that may use agricultural residues or firewood depending on the availability at home. Usually there would be a stock of branches of trees or agricultural residues like coconut fronds or cotton stalk, corn stalk or any other residue that cannot be used as fodder or fodder like straw in excess. These features have not changed over decades and the changes seem to be that on the average, the usage has improved to 4 LPG refills per year in better area of rural environment (Kar et al, 2019). The inevitability of of biomass of improper quality can be overcome by creating a market of affordable prepared biomass based fuels with appropriate specifications of size, moisture content and ash fraction all of which control the combustion process. Such a market allows also for the creation of job opportunities to several skill levels of labour.

Carter et al (2019) have conducted a study more recently on the extent of clean energy adoption (could mean natural gas and LPG) in select provinces of China in the last 20 years and draw conclusions that are parallel to what has been stated above.

Many inferences drawn here are also reflected in the African experience related by Helbig and Roth (2017) in the very interesting study across several countries in Africa. The key point made by them is that one should look beyond firewood and charcoal in order to meet the energy demands in a sustainable manner while also meeting the global challenges of climate change, a feature that resonates with the efforts being made in India in this regard.

3 Clean cooking alliance

The Clean Cooking Alliance, formerly the Global Alliance for Clean Cookstoves, was started in 2010 as a non-profit organization operating with the support of the United Nations Foundation to promote clean cooking technologies in lower and middle-income countries. Clean cooking when interpreted to include natural gas (NG) or liquefied petroleum gas (LPG) loses significance of including clean biomass cooking. The entire approach has been driven by government based promotion and top level management with testing of biomass stoves based on standards created by international agency (ISO). The question whether the cook stoves can meet the cooking expectations technically (while also minimizing the undesirable emissions) in the field has not been addressed in a manner that there is accessible scientific documentation. This inference is supported by the fact that natural convection based stoves are placed along with forced convection based systems to enable people to choose what they desire. With this approach it would be impossible to achieve the global expectations of reduced emissions from cook stoves as will be further clear from the material to follow.

4 Solid biomass and other fuels for combustion

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 rigour in ensuring dry biomass use in stoves. Cooking demands vary from domestic to community applications. Typical burn rate of fuels is about 0.8 to 1 kg/h for domestic cooking for an hour or slightly more and community kitchens may need several stoves with fuel burning ability of 1, 3, 5, and 10 kg/h. The size of the biomass - fire wood or other agro-residues will correspondingly vary with 1 kg/h using anywhere between 10 mm to 20 mm size and larger systems, a mix of 10 mm to 50 mm firewood with a mean size of 30 mm, and the larger size systems use long pieces or logs with sizes going up to 50 mm or more.

As examples of the possible biomass sources that need to be reckoned with, the fuels available from forest and plantation residues, cutting down of whole trees, wood working wastes from manual-to-automatic machines and select biomass wastes are set out in Figures 1, 2 and 3.

Figure 1 has four different classes of biomass all of which were used in a steam power station of 10 MWe capacity burning 10 to 12 tonnes per hour of biomass. This is in fact typical of many biomass based power stations. Because of the need to have fuel security, multiple biomass sources are used, only four of which are shown here. Procurement depends of final arrival price of as much of a prepared fuel as possible.

Juliflora prosopis comes from plantations that have fuel processing machines delivering sized long pieces of about 50 to 100 mm diameter and 300 to 500 mm long with moisture content up to 30 %. Chipped coconut fronds arrive with chipping done in several locations and then shipped to the site of the power plant. The plywood waste comes from a long distance and hence gets delivered in lorries. Tapioca stem in large quantities is delivered from shorter distances. These are chipped right at the site of the power plant before being transferred to the combustion system. Not all the biomass is dried and there have been questions whether drying outside is indeed superior to drying that happens inside. If wet biomass is introduced into the combustion chamber, the thermodynamics levies two penalties. Firstly, the energy for drying and raising the steam released from this process to flame temperatures is drawn from the combustion process itself. Secondly, this process will effectively bring down the flame temperature compared to what would have been obtained if biomass was dry and so the effecive heat transfer to the working fluid will come down. Thus using the heat in the exhaust to dry the fuel would be the most appropriate solution. The situation is not different in Europe and the Americas (see section 17 for more on this subject).

Also some of the agro-residues like coconut frond have a fair amount of sodium chloride. This is because salt is applied to the roots to ensure better tree growth and the uptake results in the larger fraction in the fronds. It causes corrosion to the plant hardware due to hydrogen chloride which gets released to the exhaust in the combustion process. A more appropriate strategy would be to wash the wet residues to remove the salts and squeeze the water mechanically to an extent of 50 % as is achievable and then dry the material with the exhaust.

Figure 2 depicts various wastes of processing of wood for infrastructure. Large timber processing factories will have a large amount of saw dust and furniture industries will have side cuts (not shown here), and various other types of small size wastes. All these are used for steam raising and deep frying applications in hotels and other food preparation establishments that are interested in optimizing on the cost of fuel which works to be about 20 to 40 % of the fossil fuel costs (LPG or Diesel).

Figure 3 shows many naturally available and prepared fuels for use in small combustion system - domestic and community applications. The insets c and d refer to corncobs and cashew shell wastes from processing industries. These can be directly used in the small combustion systems to be discussed subsequently. Inset e refers to prepared fuels using cow dung along with sawdust to enable obtaining a structure to the fuel. It has a low density. It was obtained by manually making balls of the mix and drying them. If very light material is in abundance, it would be appropriate to pulverise it, mix it with a binder - almost any waste wet food stock (like waste fruits, banana and waste cooked rice, and others) to the extent of about 10 %, pass the mix through a screw press not very different from what is used in food industry and dry it.

Figure 1: Biomass fuels in combustion systems of steam power generating systems, densities of 300 to 500 kg/m^3, moisture fraction up to 30 %[coconut residues have considerable sodium chloride

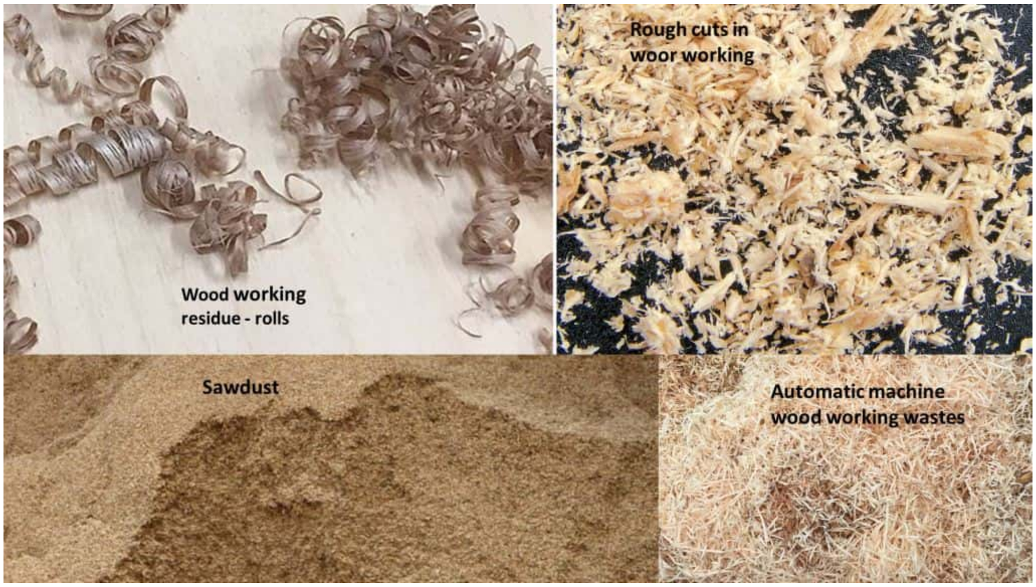

Figure 2: Wood processing based fine biomass, packing densities of 50 to 100 kg/m^3 that need pre-processing for use in combustion systems

Once dry, it can be used in continuous combustion systems of the kind discussed later since the systems do not depend on the fuel density for the operation. The only issue is that these fuels cannot be stored for long time as they would affected by fungal attack.

Density of the fuel affects directly the periodicity of the fuel feed. The highest density fuel needs to be fed at nominal power perhaps once in an hour but the lower density fuels every ten minutes or so. Larger systems that are generally for industrial need will have automated feed system. The domestic system at 1 to 1.5 kg/h throughput is in a sense more difficult to be realized since the expectations are different. Clean combustion and continuous operation have to be coupled with reducing the initial cost of the device to ensure affordability of the community benefiting from it. For the fuels shown in Fig. 3, the cost has the same trend as density since lighter fuels are found more easily and the densification process adds to the cost of the fuel. Typical cost of firewood might vary between 0.06 to 0.1 USD/kg, the cost of pellet fuels would be about double this value. Without automation, the limitation is that those who wish to use a combustion system with the low density fuel (that may be very cheap) will need to pay much larger attention to fuel feed and ash extraction with higher ash fuels. Inset f is the standard pellet fuel with seasonal agro-residues (bagasse, groundnut husk, coffee husk, sawdust, sal, celery waste, marigold waste, rice bran, and others, the choice being made to balance the cost and quality of the

Figure 3: Fuels for small combustion systems: (a) Cut tree droppings along with bark, packing density of 200 to 210 kg/m^3, (b) causarina chopped pieces, packing density of 240 to 280 kg/m^3, (c) corncobs, packing desity of 200 to 210 kg/m^3, (d) cashew shell waste - 90 to 100 kg/m^3, (e) processed sawdust-cowdung balls, 60 to 80 kg/m^3, (f) pellets of a mix of seasonal agro-residues, packing density = 600 kg/m^3, ash content of all biomass $\leq$ 5 %, drawn from Mukunda and Attanoor, 2017

Table 1: National fuel usage in rural and urban households and energy efficiency, 2010; hh = hosehold, mhh = million household, mmt = million metric tonnes, yr = year, t = tonnes, GJ = Giga 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	10.5
Others	1	2	-	-	
Total	141	66	465^{a}	$3.2^{a,b}$	$47^{a,b}$

^{a} includes solid bio-fuels only, ^{b} national averages

pellets.

5 The Indian scene on cooking fuels

The national statistics on fuel use in cook stoves and combustion systems in rural and urban environments is available in some detail for India and is presented in Table 1. This table is composed from the data discussed earlier in Mukunda et al (2010). There are differences between various studies and the data of Table 1 can be expected to have inaccuracies up to 15 %. The table also includes the use of fossil fuels and it has been thought important to examine the quality of relative usage.

The data in the table 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-residues is enormous, a fact about which *there is very little 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 cow 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 cow dung cake should address this aspect as well. Coal is used in a wasteful way and is highly polluting largely because of ignition problem. Many of the stoves are lit in the open for the volatiles to escape (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.

LPG and kerosene are more sought-after fuels and are in the upper region of the energy ladder. Hence, they are more expensive to procure, but yet, procured for use as discussed in section 2.5. They turn out to be important as reference for performance comparison. 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 last column containing the energy usage per year per household is based on the calorific values of biomass, kerosene and LPG as 16, 42, and 45 MJ/kg and on this basis, one would have expected kerosene usage (0.5 t/yr/hh) to be not so high - it should have been about 30 % higher than LPG (0.24 t/yr/hh) 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 was being 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 difference 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 cow dung cakes as 12 %. Enhancing the efficiency of the use of agro-residue based fuels and cow dung cakes must occupy the highest attention, next to which is firewood. Cow dung can perhaps be integrated into the strategy for better fuel making without any special stove design for cow dung cakes; fuels based on agro-residues and cow dung should be dealt with as a separate development task.

Lastly, it is noted from Table 1 that the average energy per year per person is estimated at 5 to 10 GJ in Ravindranath and Hall (1995) from some detailed surveys. The present estimate of 8.9 GJ/person/year (the average household in rural India is 5.3 as per the recent census documents) falls within the range obtained earlier.

5.1 Managing light agro-residues and cow dung

Most agro-residues are characterized by seasonal availability and low intrinsic and bulk density. Typically, intrinsic density varies from 50 to 200 kg/m^3 where as bulk density would be 50 to 70 % of this value. There is also substantial moisture (up to 50 %) at the time the material is harvested. The very fact that densities are low permits loss of moisture even in open air storage, the extent of loss depending on the ambient conditions. Transportation and combustion are affected by these aspects. Drawing from the practice of firewood transportation, it is understood to be economical to transport about 10 tonnes of firewood over hundreds of kilometers, shorter the distance better. A truck carrying 10 tonnes of firewood whose typical density is upwards of 500 kg/m^3 can carry less than a few tonnes of agro-residues economically. The region to be covered to maintain a continuous supply of a variety of these residues becomes large, many times larger than economics can support. Hence, densification is an important element in the process. A question then arises - is it not good enough to densify the material to as much as firewood (implying about 500 kg/m^3)? The answer to this question comes from the stove that uses this material. Approaching high efficiencies of a LPG stove demands that the combustion volume be brought down to as low a value as possible. This can be obtained by increasing the density of the fuel. Also in a stove with a fixed storage volume for the fuel like the one considered here, increasing the density helps in reducing the overall chamber volume that would have benefits of lower inert material content and associated heat loss.

A question that arises next is the level to which the material must be densified. Here, practice in industries suggests that binderless briquetting achieves a density of 1000 to 1100 kg/m^3. 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 to 50 mm long to obtain good packing density. Producing pellets of this size at large throughputs in an economical way has many challenges in the process as well plant throughput sizing both of which have not been addressed adequately in India, yet.

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 binder-less briquetting and are typically about 600 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.

6 General Observations

The issues brought up in the above sections can be summarized as below:

1. Traditional practices on the procurement of biomass via felling of trees continue in most of Africa and parts of south east Asia with agricultural residues constituting a small fraction. In India and China, movement towards the use of agricultural wastes as domestic fuel has occurred significantly, but not necessarily appropriately in terms of indoor air pollution or environmental related factors.

   Many establishments and street side hotels use wastes from saw mills and furniture industry, but this usage ignores moisture and size related problems. When the problems associated with them become significant, they shift to fossil fuel based combustion systems temporarily because affordable dried fuel supply is non-existent.

   Both these aspects can be considered as new market and rural job creation opportunities for dried and sized biomass fuel based on tree fallings and excess agro-residues throughout the year thus mainstreaming biomass as a fuel.

2. The use of charcoal in the existing domestic stoves across the World produces more indoor pollution particularly of carbon monoxide at levels very much more than with biomass (reasons discussed in section 15) and has been known as a serious health hazard. Further, the efficiency of production of charcoal from biomass is very inefficient and the thermal efficiency in cook stoves is about the same whether one uses wood or charcoal (on the average). This means that through the production of charcoal and use in cook stoves, the amount of biomass is at least twice as much as is needed for cooking. While all that is written about the subject described in the above paragraphs refers only to the inefficiency of charcoal production, its irrelevance to meeting the cooking demand is not recognized - nearly World over.

   This is a serious problem since one cannot solve a problem if it is not even recognized.

3. Suggestions for shifting to electrical cooking as a new option has been suggested (Batchelor, 2019) at least for Africa. These suggestions that may be followed by UK department for international development meant for Africa is strongly stated based on certain crucial facts that seem very weakly founded. The data

that they project indicating a value of 0.5 kWh for cooking is devoid of technical details and as will be shown later, the energy required for cooking in an average home is between 6 to 9 kWh (about 1.5 to 2.5 kg dry biomass) per day. Also, it must be recognized that traditional practices cannot get shifted drastically unless the entire community realizes that this direction has an intrinsic usefulness.

4. The suggestion to shifting to electricity arises from fulfilling the need of a consumer to obtain energy at the turn of a switch. LPG stove operation works similarly. Opening the valve and lighting the gas helps start cooking. Usage of liquid fuels in kerosene stove works close to that of LPG. Cooking with biomass is beset with several issues. Availability of dried sized fuel is the key issue. The family has to source the fuel of varying sizes and moisture and try to dry the fuel and size it for proper usage. Even if fuel is procured from the market, there is no guarantee that it meets the specifications on size and dryness fraction. Pellet fuel has a similar price inaccessibility issue. Biomass based charcoal as the fuel has been found as a possible answer in parts of urban Africa, East Asian countries and north east India even if the costs border on being unaffordable. More seriously, charcoal combustion is an invitation to unseen indoor air pollution.

   If this complex matrix has to be broken, an affordable and accessible source of biomass fuel along with clean combustion system needs to be found. Until it is found, the role of clean cooking alliance will not be complete.

7 Combustion issues of solid fuels vis-a-vis liquid fuels

Both liquid fuels like kerosene (or diesel) can be delivered in plumbing under mild pressure and sprayed into a combustion zone as fine droplets aiding the combustion process. Gaseous fuels like natural gas or LPG can be piped and delivered through jets or orifices in a uniform manner along with air for creating clean combustion. The central problem of dealing with biomass for combustion would be to account for the widely varying properties of the feed stock acting as a fuel. If biomass can be converted to combustible gas as it happens in a gasification process, one can deal with combustion more simply. Once the producer gas is generated, it is simpler to cleanly burn the gas (gas from the air-gasification process) than natural gas because it has already oxygen in it (CO, which is 20 % of producer gas contains O atom). But any gasification process demands prepared fuel in terms of input properties - moisture must be limited to less than 10 % (certainly not more than 15 %), the shape and size must be uniform, both of which need sizing machines or pellet making machines to typically produce material of 5 to 25 mm diameter, 25 to 50 mm long. Another qualification is that the waste biomass is to be handled in a manner that infusion of fine inorganic material in the form of mud, sand and grit be eliminated and in any case limited so that the ash content of the solids qualifying for combustion should have ash fraction no more than 15 %. This expectation is to obtain better heat release is directly deduced from the fact that the presence of inerts reduces the calorific value of the fuel and its absence restores the calorific value of native biomass. These is also an issue of ash fusion that occurs because of the presence of potassium and sodium salts that come from inorganic sources. Both aspects namely, limiting inorganic material and the fraction of specific salts are central to smooth operations (see section 11.9 for more details).

The gasification process in itself is involved and can only be deployed whenever community demand of piped gas is appropriate. Handling individual demands is better dealt with by direct combustion process much like a cook stove, but engineered towards higher performance coupled with low emissions, keeping in mind the affordability of the community to be serviced. The common perception is that biomass combustion in domestic stoves is smoky and/or sooty and therefore biomass is not the appropriate choice for domestic stoves. Thus, there is inevitable need to explore and develop combustion processes that account for shape and size aspects more generously than expected of the gasification process and deliver smokeless and efficient performance. In view of the above situation, it is important to explore the biomass combustion alternative with multiple options - in terms of fuels and power levels.

7.1 Smoke or soot in biomass combustion - why?

One of the elementary questions that needs to be answered in simple terms is related to the thinking that biomass combustion almost always implies smoke and soot. Smoke is essentially the presence of un-burnt volatile compounds issuing out of the surface of biomass undergoing heating in the presence or absence of air. In the absence of air it is called pyrolysis and in the presence of air it is termed oxidative pyrolysis. If the mixing with air happens at temperatures up to 400°C, no oxidative exothermic reactions occur and one gets smoke. Soot is observed when the fuel vapours and air burn up under conditions that have insufficient air. The amount of air required for combustion is typically 5 to 7 m^3 air for every kg biomass and if the combustion process that occurs locally in the volume of the "flame" does not have enough air to oxidize the fuel locally, then, one gets fuel rich products called poly-aromatic hydrocarbons that end up as soot which is largely carbon.

If one were to allow self-aspirated or free convective air supply as in a classical wood burning stove, then the fundamental flow combustion instability will lead to cyclic variations of air flow into the combustion system depending on the fuel evolution rate and location on the grate of a combustion system. The mis-match between the fuel evolution rate and the air available for combustion leads to inevitable changes in air-to-fuel ratio all the way from very lean to very rich conditions. If it is fuel lean, one gets smoke and if it is fuel rich, one gets sooty conditions. It may actually turn out that one part of the solid fuel experiences lean and another rich conditions. Thus, one can get profuse irritating smoke as well as soot-coated vessel. These fundamental features have rarely been explicitly stated and of course not addressed in so far as domestic cooking applications are concerned. It is also true to say that commercial and industrial applications always have blower assisted air supply for volatile generation (perhaps complete or partial gasification) and the combustion of the fuel rich gases normally termed as primary and secondary air supply.

8 Practical free convection stoves

Nearly all the domestic cook stoves over the world are free convection driven. The resulting flame is always called a fire - cooking fire is a well used phrase for this class of stoves. There is an enormous literature on the traditional stoves. Aprevecho centre in the USA (www.aprevecho.org) presents a lot of information from World-over in an anecdotal style with a large number of stove enthusiasts participating in its efforts, the most significant of which are the testing of stoves. It is not obvious that calibrated set of results with analysis and recommendations are set out as a result of the efforts, because testing the same class of stoves and obtaining slightly different values is not going to alter the understanding or improve the quality of the stoves.

Figure 4 shows the principle of a chimney based fixed biomass stove and two examples of stoves. The traditional fixed biomass stove is a classical brick and mortar construction in the dwelling and as seen here, it is a single pan system. The fuel that may be firewood or agricultural residues can be introduced through the fuel loading port and lit. The cooking vessel above it will receive the heat. The exhaust passes through a chimney whose outlet will usually beyond the dwelling to ensure that the exhaust does not cause indoor air pollution. Also, the chimney will provide the draft required for the induction of air for combustion.

The figure next to it is a two pan Chinese design a particular design that uses the heat in two stages before exhausting the burnt gases into the atmosphere through a pipe at the top region. The figure below is a three pan stove designed by Lokras and team (Lokras, 2012) that aims to get a high water boiling efficiency of about 40 % from the three pan system. Over 1.5 million stoves were built in the state of Karnataka, India with thousands of trained masons to build them in the dwellings. A large effort was subsidised by the state Government.

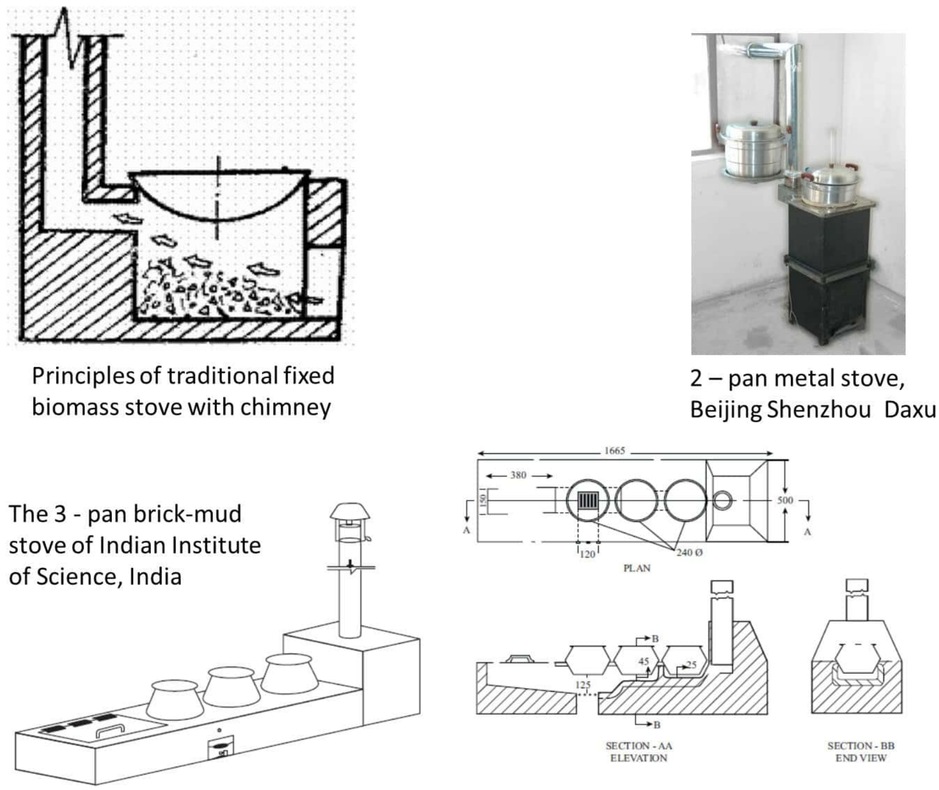

Figure 4: A sample of traditional fixed "improved" chimney based cook stoves across the World

The problem with these designs is that the stove in its normal operation will occasional run fuel rich due to differences in the nature and amount of fuel loaded, largely due to the cook's impression that the food cooks faster with higher loading of fuel. The rich operation leads to the generation of tar that deposits in relatively cooler areas. This builds up over a time and reduces the chimney draft and so on several occasions the fire comes out of the fuel feeding port itself. This, of course, contributes to indoor air pollution that is not realized except when measurements are made. Further, these designs demand that the vessel seating over the stove must be sealed over the contact region. While this may very well happen in the early stages when the stove has been built freshly, but over time, there will be gaps created due to wear and tear. Air can leak through this region contributing to local cooling and also reduction in the pumping potential of the chimney.

As different from the above, Fig. 5 refers to portable mud and metal stoves. Two types of mud stoves from Laos and Guatemala are set out. There are several hundred

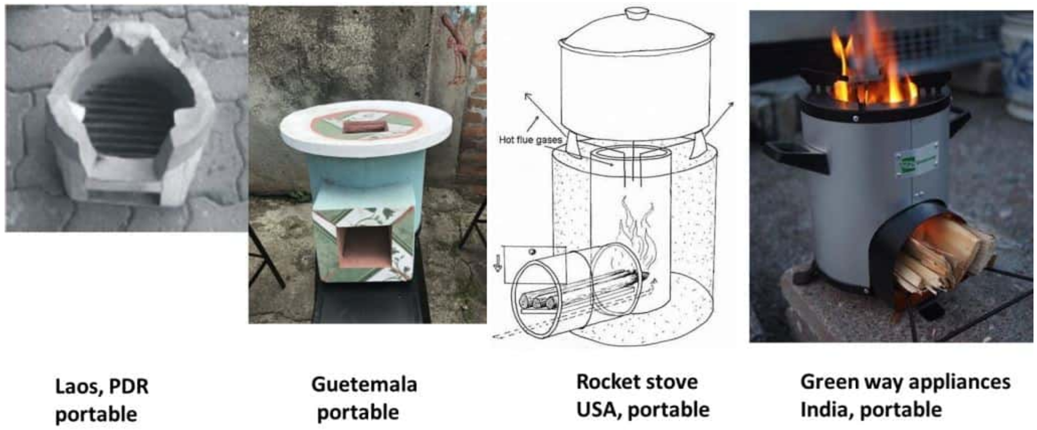

Figure 5: A sample of traditional portable "improved"mud and metal cook stoves across the World

variants of this class of stoves across all countries. The design of the rocket stove made famous by Dean Still of Aprevecho.org, USA is the third figure. The last figure refers to a similar design built and sold in large numbers by M/s Greenway appliances. There was an earlier metal version called Priyagni, sold about a million in India in a subsidy program launched by the ministry of Indian government. A more compact stove called Swosthee, short form for single pan wood stoves of high efficiency, was developed by Mukunda et al (1988) and some hundreds were built and tested in domestic environment. Nothing beyond understanding the way the consumers are likely to use the stove some times very different from expectations was what was learnt from the field study.

Biomass of various sizes including agricultural wastes are introduced into the stove in any way that the cook decides to do and combustion proceeds with no control on the air-to-fuel ratio and the combustion process can occur from lean to rich conditions. The only time combustion appears good is when char combustion takes place, particularly towards the end. Occasional insertion of a firewood stick would raise the power and this will quickly settle back to the lower power level with charcoal combustion.

Figure 6 refers to a traditional sawdust stove that has been prevalent over the last hundred years all over the east - India, China, Thailand, Indonesia, Sri Lanka and others. It is simply a annular tamped sawdust in a container with a side tube towards the bottom linking to the central opening from the side as shown in the inset d. When lit, air drawn by free convection flows through the central port and forms a flame over the top region. Because it is free convectively driven, many issues of

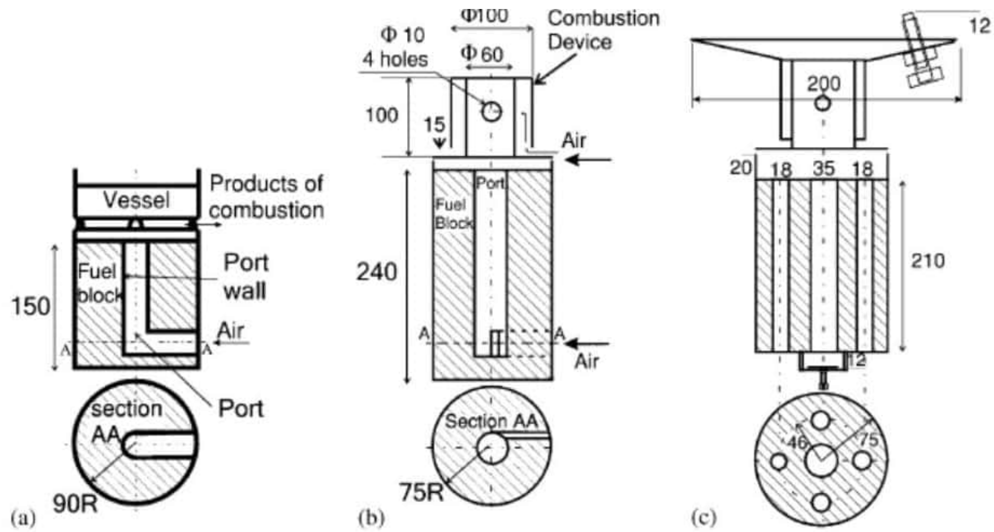

Figure 6: The design variants of sawdust based stove

varying A/F remain, even though the combustion process is better since the bed is not disturbed during the operation. The operational aspects as well as the technical aspects of combustion behaviour have been examined by Mukunda et al (1993) providing the relationships between the power and the controlling geometric parameters and by Dixit et al (2006a, 2006b) on the thermochemical behaviour inside such stoves. They also have tried out geometric variants as can be noted in b and c of Fig. 6 to get desired burn profiles and better combustion behaviour.

8.1 Unsteady combustion in free-convective mode - why?

It is important to understand the physics of the free convective mode of combustion. The air flow induced into a fire is dependent on the column of fire because the hot gases are lighter. To appreciate this more precisely, we examine the densities at the ambient and fire conditons. The density at ambient temperature of 300 K is 1 kg/m^3 (ρ_{cold}) and at fire temperatures of about 1000 to 1200 K, is 0.3 to 0.25 kg/m^3 (ρ_{hot}). Thus, the ambient air has a natural tendency to displace the hot gases to larger heights. The flame height scales as the size of the fuel source (hearth size, d, say). The velocities caused by free convection scale with d as $\sqrt{(\rho_{cold}/\rho_{hot} - 1)gd}$ where g is the acceleration due to gravity. We also recognize that the flame is caused by chemical reaction between the gaseous fuel vapour coming off the solid fuel and ambient air. As soon as the combustion is over, the flame height tends to drop, while fuel vapours continue to emanate from the solid fuel. This heat is not sufficient enough to draw

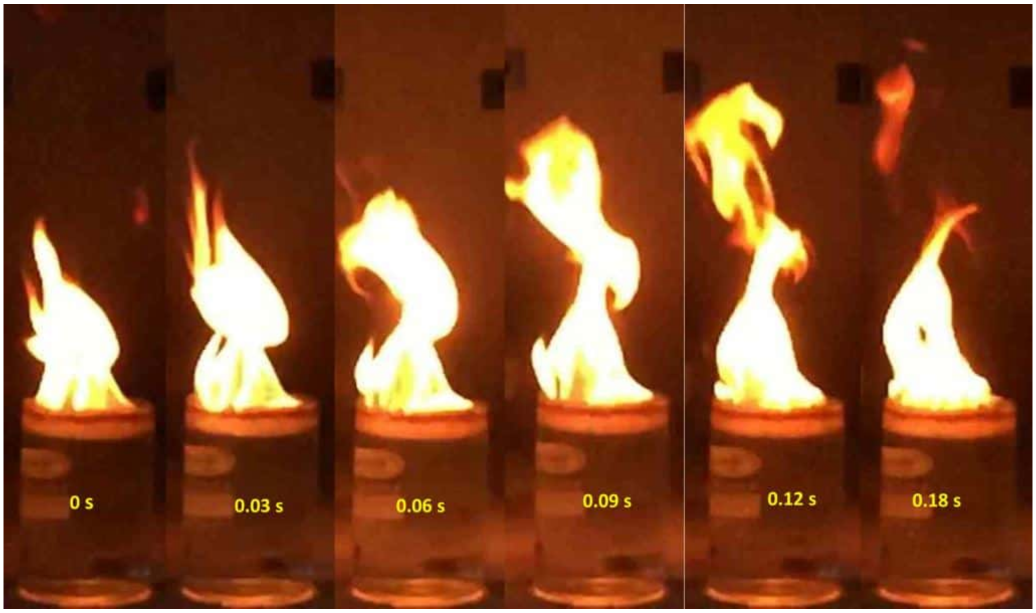

Figure 7: The pulsating fire over a 90 mm diameter pool fire of n-heptane

immediately the amount of air required for it to be burnt. It takes time to build the air flow velocities in the quiescent surrounding air for the flow to become available for combustion. *This lag leads to an instability*. When the size of the fuel source is very small, say a few mm, the time scales are not different and the flame is steady - like in a laboratory spirit lamp or a small kerosene wick lamp. As soon as the size increases, the imbalance in the rates of air ingestion and heat release leads to instability that can be observed as periodic puffs of flames, a subject studied extensively in the area of fire research (see for instance, Drysdale, 1999). The periodicity of the puffs varies as $\sqrt{d/g}$. Thus, larger combustion systems will have longer periods of puffs. Figure 7 shows the typical flame up-growth and sudden fall back features of a n-heptane pool fire of 90 mm diameter. The pulsation frequency of 5.5 Hz (corresponding to one period of 0.18 s) occurs due to the phenomenology described above. A measure of the free convective driving potential can be obtained if we note that humans can blow air at about a m/s and the free convective velocities are in the range of about 0.2 m/s. Hence, the smallest of ambient disturbances more than these values 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 like in the rocket stove (or in the sawdust stove described in Fig. 5) 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" lead to widely varying air-to-fuel ratios locally. This kind of a variation reduces the peak flame temperature most of the time

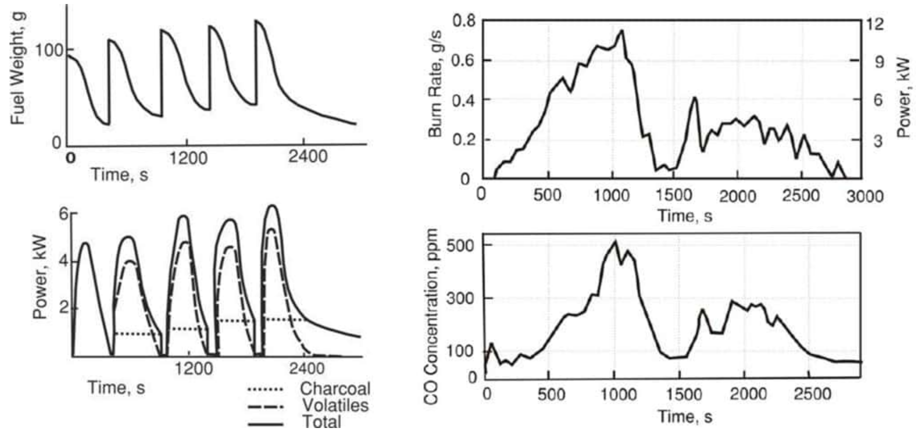

Figure 8: Variation of power and CO emissions in free convection stove, Left - from Prasad et al, 1985, Right - from Ballard and Jawuerk, 1996

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. As discussed earlier, this is related to the incorrect perception that higher loading leads to faster cooking. Getting good emission performance from such stoves is usually a difficult task. Thus, *laboratory test results and operational data from realistic environment can be widely different*. Much of the current debate that is going on with regard to the standards and protocols for testing stoves arising from the fact that the lab tests are different from real experiments is due to this fundamental aspect of the free convection stove; by design, the efficiency as well as emissions are dependent on the user and the ways the stove-fuel combination is used.

9 Emissions high in free convective stoves - Why so?

The results of studies on free convective stoves from the work of Prasad et al (1985) and Ballard and Jawuerk (1996) are set out in Fig. 8. The left side figure shows the thermal behaviour of the stove operation. Wood loading increases the volatile generation rate and soon after their rate comes down, the power also comes down. The charcoal that burns at much lower rate contributes to about 25 % power. The right side figure shows that the CO emissions increase because of increased burn rate. Occasional departures in the relative relationships are to changes in air-to-fuel ratio in the combustion process. The emissions behave the way they do because the stove is unable to draw enough air by free convection and deliver it to the pyrolysed part of the fuel for completing the combustion process and so, this leaves the combustion process nearly always fuel rich. It contributes much more to the enhanced emissions of CO, as well as many other un-burnt products of combustion (like poly aromatic hydrocarbons). The only way to reduce the undesirable emissions is to introduce air in a manner that all the fuel parts receive the necessary oxygen (from air) for complete oxidation. This is the crucial reason for the development of forced convection combustion devices for domestic applications. This is described below.

10 Specifications of a stove

It is a classical engineering practice, building of any device begins after setting down the specifications. In so far as cook stove is concerned such an approach has rarely been sought and more designs turn out to be evolutionary with trial and error approach. Therefore, it is important to deduce how much of energy and power one needs for each of the required thermal operations and in particular for a domestic cooking solution.

We will take first, domestic cooking. Based on a survey, it is taken that the family size is 4 and they cook 1 kg rice with 2.5 kg water, 0.25 kg lentil and 0.3 kg potato with 1.65 kg water, 0.25 kg thin wheat bread (chapatis), and 0.2 kg of fried vegetables. The amount of fuel needed for these as estimated from experiments and observations (see Mukunda, 1988) is (0.25 + 0.35 + 0.2 +0.2) = 1 kg sun-dry biomass with a calorific value of 15.5 MJ/kg to be completed in an hour. This gives us therefore, a measure of the power of the combustion system needed for a cook stove - 1 kg/h of sun-dry biomass burning system. If a two-pan system is designed for simultaneous operation, one would need a 1.5 kg/h class system. Table 2 lists the specifications.

Community cooking applications require larger power combustion systems that can operate for about 2 to 3 hours over several stoves, at least 2, with capacities of 3 to 6 kg/h. The assumed over efficiencies will be about 30 % for free convection based combustion systems, $45 \pm 5\%$ for forced convection 1 kg/h systems, 55 ± 5 % for forced convection well designed systems with large enough vessels (see section 13 and specifically Fig. 37 for more discussion on efficiencies).

Most domestic stove developments have occurred because of enthusiasts around unspecified objectives and the system is altered in relation to local perception, many aspects already described in section 8. Forced convection combustion systems have needed more detailed understanding of the physics of the process to account for the variability of the shape and size effects of as received biomass. What will be described in the following has the specifications outlined above as the basis of new approach to clean continuous combustion systems whose basis draws upon batch system operation

Table 2: Parameters for a domestic combustion system for cooking

Parameter	Observation
Power	0.75 to 1.5 kg/h, 3 to 6 kWth
Efficiency	35 % or more
Fuel	Prepared fuel flexibility desirable
Smoke	Smokelessness essential
Soot	Sootless operation desirable
Operation	Control very desirable
Appearance	should be aesthetically attractive
Price	Optimised to ensure affordability

described first.

For industrial related operations, one sets down the thermal energy demand, and design a suitable biomass based combustion system with a chosen value of the effective efficiency.

11 Clean combustion batch mode - principles and practice

Batch burning forced convection stoves are based on gasification principles. Gasifiers are essentially devices that enable converting solid fuel to gaseous fuel by a thermochemical conversion process. This process involves sub-stoichiometric high temperature oxidation and reduction reactions between the solid fuel and an oxidant - air in the present case. This is arranged such that air and the gas pass through a fixed packed bed.

11.1 Brief history

The gasification know-how has a long history; it became particularly important in the European scene during the World war II when fossil fuel availability was scarce. Research and development into gasification process came to a low after fossil fuel availability became normal and their prices low. The area has become active in the last thirty years particularly in oil importing countries like India. Research relevant to the objectives of this paper 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 (see Bhattacharya, 2005), the scientific investigation was conducted by Kaupp (1984). In this reactor,

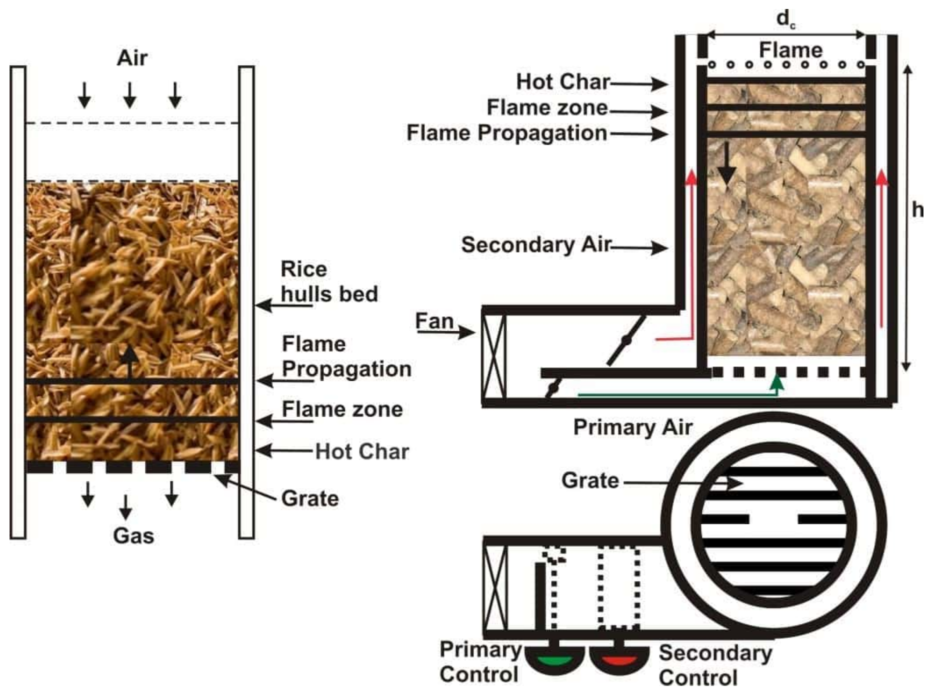

Figure 9: The left side of the figure is schematic view of a rice hull gasifier. Note that the air flows from the open top towards the bottom. The right side is a schematic of a reverse downdraft gasifier stove where the gasification air flows from bottom to top

shown on the left side of Fig. 9, one can use biomass like wood chips, and pellets apart from rice hulls for which it was first conceived. If now the reactor is 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 the top surface with ambient air or with additional air supplied towards the top. Such a configuration, shown on the right side of Fig. 9, termed reverse down-draft system (REDS) constitutes the essence of a gasifier stove. It has been termed more popularly as top lit up-draft system (TLUD) in the USA.

An important consequence of this mode of operation is that the 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. 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

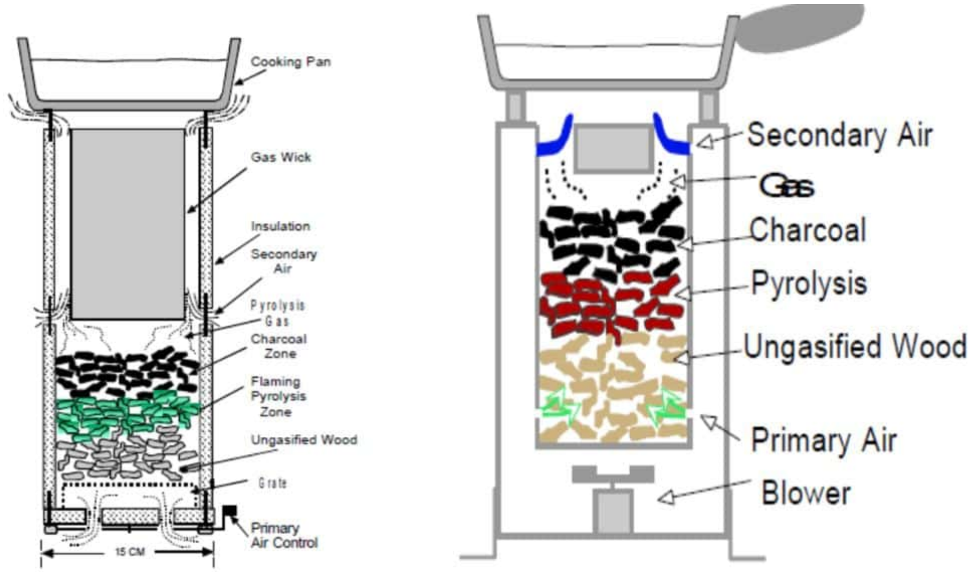

Figure 10: The free convective design and fan based model schematics of Reed et al, 2000 drawn from their work

1100 K and will be composed of combustible gases CO, H_2, CH_4, and others like CO_2, H_2O (as gas), some higher hydrocarbons and N_2. The combustible 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 an 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, 2000). These are shown in Fig. 10. These designs allow for the use of finer pieces of biomass and pellet fuel. The performance of the free convective design is not very distinct from the versions discussed earlier in terms of thermal or emission performance.

In the above designs, it is not clear what the role of gas wick is. Reed's conception of the fuel in these stoves is largely wood chips and the early free-convective design was supposedly for developing countries and the subsequent design with forced convection formed the basis of camp stove and this is indeed how it got marketed. While the broad principles were clear at this time, the aspects of process optimization and development of components needed to be addressed to deal with the affordability issue in emerging economies like India with fuels depending on agro-residues rather than wood chips. Also, it is important to recognize that the design allows only a batch operation and all the fuel intended for the burn duration should be loaded in the beginning.

Once lit, the burn rate and power are controlled by the air flows in the case of forced convection system. It may be asked at this time, what would happen if additional biomass is loaded to obtain more thermal power, after the initially loaded biomass burns up to char. The combustion process of this biomass that receives heat from below will get ignited all over and operate similar to normal cook stove conditions - power going very high with inadequate air and so the combustion process has larger undesirable emissions. Thus, it is important to avoid loading fresh fuel into the system that has just burnt up the fuel and is still hot. The development of this design for cooking needs high density fuels to enable packing them in a smaller volume, a subject discussed in section 11.4.

Even though the work at the IISc laboratory on gasification systems had begun in 1988 (Mukunda et al, 1988) and reached reasonable maturity by the end of nineties, the work on the development of stoves of high efficiency using reverse down-draft stove concepts began in 1999 with a study to determine the dependence of various parameters on the water boiling efficiency and emissions with several agro-residues using laboratory based air supply. One of the key drivers for the development of these laboratory systems into a product was the availability of a small fan working on a storage battery. The idea of building a domestic stove became meaningful when the fans for supplying air were being built in numbers for computer applications and at this stage, low power fans could be obtained or built at less than 5 USD per system including the electrics.

11.2 Physics of the combustion process

The physics of the operation of batch stoves has been explored in depth in Varun (2012) and an important operational behaviour drawn from this work is illustrated in Fig. 11. The left side of the figure is a plot of fuel mass flux as a function of superficial velocity of air through the fuel bed. The superficial velocity, V_s is defined as the volumetric flow rate of air divided by the empty reactor cross sectional area. The data points are drawn from a large number of experiments of earlier studies. The black dotted lines constitute the mean behaviour. The behaviour is classified into three broad regimes. Regime I constitutes gasification, Regime II, combustion and Regime III, extinction. In regime I, the air flowing through the bed is inadequate to oxidize the fuel bed area near the top region and so the burnt gases react further with the char obtained after volatiles have got released and so, one obtains fuel rich gases. This is the gasification regime. In regime II, the combustion regime, the air flow rate through the bed is such that the char is also oxidized into CO and CO_2 with increasing conversion of carbon till only one layer of carbon will be left at the end of this regime. In regime III, between 0.4 and 0.5 m/s, the heat drawn away by the air becomes far more than heat released by combustion and so, the flame extinguishes. Regimes I and

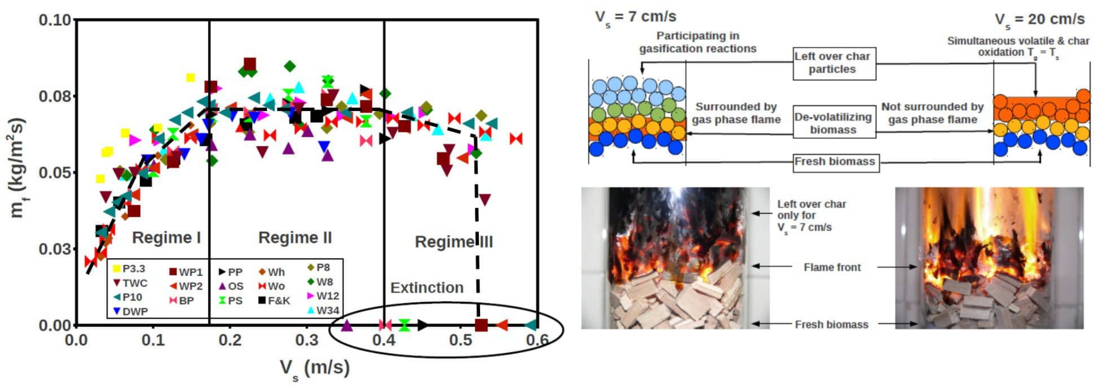

Figure 11: The plot of the fuel mass flux as a function of the superficial velocity of the air flow through the bed on the left side and depiction of the burn behaviour at two different superficial velocities corresponding to regime I and Regime II, drawn from Varun (2012)

II have been studied in great detail by Varun (2012).

11.3 Gasification air-to-fuel ratio

Simple experiments were conducted in which the air flow rate and the fuel burn rate were both measured by mounting the model combustion system on a balance. Table 3 shows the gasification air-to-fuel ratio (A/F) and the bed temperature (T_b) measured for three different primary air mass flow rates. This simple result obtained from air flow rate ($\dot{m}_a$) and mass burn rate of the fuel ($\dot{m}_{fuel}$) computed from mass vs. time data confirms the known fact that the A/F of gasification is constant irrespective of the fuel consumption rate in the range of flow rates considered. This condition is required for obtaining gas of highest possible calorific value (Kaupp and Goss, 1984). It is important to recognise this fact because the A/F is not 1.5 for all range of air flow rates as shown in Reed et al (1999). Therefore, this serves as a check for optimal performance of any gasifier stove. The bed temperature increases with increase in the air flow rate. These two phenomena, namely, constant A/F and increasing bed temperature, are consistent with the internal heat balance in the gasification process. As the air flow is increased, the heat release rate will increase because more of the pyrolysis products are burnt. But this will not increase the temperature of char bed directly because the endothermic reduction reactions (C + $CO_2 \rightarrow$ 2CO and C + $H_2O \rightarrow$ CO + H_2O) will aid reduction in the temperature rise. Also the amount of gas passing through the char bed undergoing endothermic reduction reactions will increase and therefore, the consumption of char will increase. This net effect results in a constant

Table 3: Gasification air-to-fuel ratio, A/F and bed temperature (T_s) with wood as the fuel, $\dot{m}_a$ - air flow rate, $\dot{m}_{fuel}$ - fuel consumption rate in flaming mode, Varun et al, 2011

V_s cm/s	$\dot{m}_a$ kg/h	$\dot{m}_{fuel}$ kg/h	A/F	T_s K
3.2	0.9	0.60	1.5	996
3.8	1.1	0.72	1.5	1096
5.3	1.5	0.98	1.5	1206

A/F even with the increase in the gasification rate (or mass burn rate of the fuel).

The fuel mass flux increases nearly linearly in early stages and saturates at $V_s \sim$ 0.2 m/s. The maximum fuel flux that is possible is about 0.08 kg/m^{2}s (or 300 kg/m^2 h). Interpreted simply, it implies that about 300 kg/h can be burnt on a grate of 1 m^2. The fuel mass flux is also called fuel loading flux, FLF, in engineering terms. Typically, at a superficial velocity of 4.0 cm/s, the air flow rate (we must remember this is bottom air or primary air or gasification air) in a 100 mm diameter combustion chamber will be 314 cm^3/s. This works out to about 0.31 kg/s of air with density taken as 1 kg/m^3. The air-to-fuel ratio in regime I is 1.5. Hence, the fuel flow rate becomes 0.2 g/s or 0.72 kg/h. The fuel loading flux, therefore, is 100 kg/m^2 h. One can raise the superficial velocity by increasing the flow of bottom air and obtain higher power. The air-to-fuel ratio increases as the superficial velocity, V_s increases, to near-stoichiometric value ($\sim$ 6).

The right side of the figure shows actual photographs of the combustion scene at 0.07 m/s towards the left part of the inset and at 0.2 m/s on the right side of the inset. The difference between the two behaviours (which is also schematically depicted above the figures) is that at the lower superficial velocity, there is residual char left on the top of the bed and at 0.2 m/s, not much char is left. In fact this magnitude goes down as V_s is increased to 0.4 m/s and as it crosses that value the entire combustion zone becomes very weak till the flame gets extinguished. The scatter in the entire data is contributed by low density biomass also being a part of the studies by several investigators (see Figure 1 in Varun et al, 2013 for the details of studies leading to the data). There are other important features related to the data plot. Domestic systems use V_s in the range 0.035 to 0.1 m/s, more typically of 0.05 m/s. Below the lower limit, the flame is very weak largely due to lower reaction temperatures. In the regime indicated the process is satisfactory with increased flame temperatures up to 1200 K at the highest values of V_s. Further increases of V_s are not encouraged even though the gasification process generates very good gas because at these velocities, particle carry over will be large.

Despite the availability of clean burning forced convection stoves, free convective stoves were and even now, are considered inevitable because of the i) 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, ii) use of any forced draft that requires electricity is seen as difficult and/or unavailable. The point (i) needs to be challenged given the variable and distinctly poorer performance on efficiencies and emissions that have been observed and recorded (to be brought out subsequently). As far as point (ii) is concerned, improvement in electricity and infrastructure and technology of smaller fans and power sources has given the real option to provide forced convection in the stove designs to improve performance and reduce emissions. All these do 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.

11.4 Considerations for the practical stove

The geometric parameters of the stove relate to the diameter and the height of the combustion chamber. These were to be decided based on the following considerations.

The power level of the stove was set at 3 kWth amounting to a nominal pellet fuel consumption rate of 12 g/min (720 g/h). Based on a measured pellet bulk density of 550 kg/m^3, a fuel loading volume of 1.3 liters would be needed. This implies that if fuel of higher density is loaded, one will get larger burn time. On the other hand, if wood chips of a bulk density of 200 kg/m^3 are loaded (260 g), the burn time of the stove will be 25 minutes. Thus, while the stove will operate with many fuels in the form of small pieces, the functional role of cooking will be met with fuels with bulk density more than 450 kg/m^3. This is the crucial reason that the choice of pellets was considered very essential for an optimal cooking solution.

In order to make a choice of the combustion chamber diameter, two consistent view points were to be synthesized. The first one was that the primary airflow had to be about 1.5 times the fuel consumption rate for the gasification process. Hence the air flow rate would be 18 g/min. The other parameter of importance is the superficial velocity through the combustion chamber. If this was large (say, of the order of or more than 0.1 m/s) then particulate carry-over would be large and this would directly affect the particulate emissions from the stove. If the velocity was too low (say, less than 0.04 m/s), the combustion process in the char mode could either be extinguished or worse,

Figure 12: The actual stove built by BP, India and marketed in several states in India

so weak that CO emissions would be large, perhaps beyond acceptable limits. The choice of 0.05 m/s for superficial velocity was made after some trial studies. This would correspond to 95 mm diameter. Thus the choice of combustion chamber diameter between 95 to 105 mm would meet the objectives of power, burn time, and minimum emission of particulate matter.

A second view arose from comparison to a typical gas stove burner; this has an outer dimension of about 100 mm. Since these stoves were used very efficiently widely, it was thought prudent to make this choice. Hence, the inner diameter was chosen as 100 mm.

The air for combustion of the fuel rich gases was provided above the top of the bed. The amount of air (secondary air) that had to be provided here constituted 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 design with 12 g/min of burn rate, the primary air is 18 g/min and the secondary air would be therefore be 54 g/min. This was supplied through a large number of holes of small diameter towards the top region. In the design set out, 18 holes of 6.5 mm dia (an area of 597 mm^2) were provided. This led to an inward air velocity of 1.8 m/s through the holes. This criticality of this air flow was more towards determining the emission rather than efficiency. For, if this air flow was inadequate, some part of the air from the ambient atmosphere would be needed to complete the combustion; but the oxidation of carbon monoxide in the product stream would be very slow. Hence, the provision of a slightly larger secondary air flow was not expected to affect the performance. Also, the fuel pellets made from a wide variety of agro-residues could not be expected to have the same CHNO composition. As such, some variations in the stoichiometric air requirement could be expected; thus, if by design a slight excess air was introduced, it could be thought of as accounting for these variations in limiting the CO emissions.

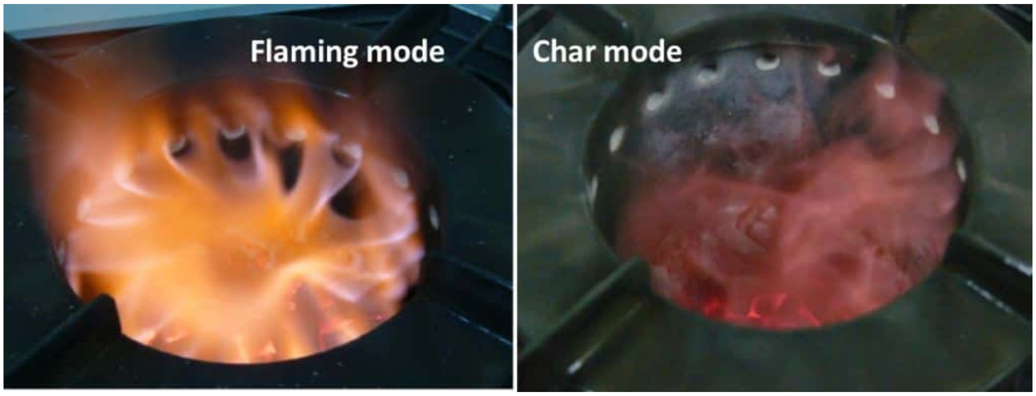

Figure 13: The flaming and char modes of combustion in Oorja, 0.75 kg/h system at the same air flow rate

It took about an year of industrialization process before elegant looking system was built. Figure 12 shows the 750 g/h pellet burning stove produced by BP, India. It has ceramic walled cylindrical chamber that assures long life. The holes seen towards the top region deliver air blown by the 1.5 W fan. The grate at the bottom holds the pellet fuel and about 60 to 80 g of ash collects over it and is dumped out after several hours of operation during which time the stove cools down. The flame comes in horizontally from around the air jets all around, comes towards the centre, undergoes some recirculation before going up to deliver the heat to the cooking vessel. It was marketed as a clean combustion system with support from British Petroleum to over 450,000 families under a large program designed to promote these stoves in which the pellet 25 kg pellet bags were sold at Rs. 5/kg ($\sim$ 7 US cents/kg) in the years 2007 to 2010.

The flaming and char mode combustion behaviour are set out in Fig. 13. The flame track in the flaming mode is around the round holes through which air is entering radially inwards. The hot gases come to the centre and around this area, a part of it recirculates downwards and part goes up. The part that goes down recirculates and enhances the heat transfer to the surface of the char which is already red hot, and the recirculation improves the combustion process because of greater residence time in high temperature environment. The surface temperature is about 1000 K at nominal operating conditions.

Continuing with the same air flow settings, the combustion in the char mode is weak. One can see the red hot char inside with a weak dancing flame inside the combustion chamber. This is because (a) the volatiles that provide lot more combustible gas flow rate (and a larger flame) are exhausted and (b) the char surface area is coming down with oxidation by air. Hence, the gasification products of char are much less energetic. To add to this, is the secondary combustion air, part of which recirculates and adds to the cooling effect. In fact the burn rate becomes about a quarter of what happens in flaming mode. This feature is not inconsistent with the projected cooking cycle demand of higher power for boiling and lower one for simmering. Even so, if greater power in the char mode is needed, increasing the air flow rate enhances the char combustion rate (much like the char burning brighter when you blow air over a red hot char).

11.5 In-situ combustion stove vs. gasifier stove

Another stove design that underwent limited dissemination is the Phillips in-situ combustion stove where the air flow is obtained from a small fan run with thermoelectric device. The stove was well engineered and elegant even though expensive. The use of thermoelectric device was largely responsible for the high cost. One would need to add a small amount of fuel that could occupy the bottom region of a small combustion chamber and after it nearly burnt out, one would need to add some more fuel. The periodicity of loading was small. The combustion process was not different from a furnace in principle. One supplied enough air for combustion directly around the fuel zone so that some parts of the fuel would undergo volatilization and the volatiles will burn with the air around, other parts that have become char will also simultaneously be oxidized. This is also true of metal based free convection stoves, where the air flow occurs through the grate and over it just from around a chamber (of short height) to complete the combustion process. While direct combustion systems are common at large power levels where fuel feeding can be automatic and combustion management is relatively easy, at small throughputs like in a domestic stove, fuel loading has to done at frequent intervals (typically every few minutes apart) manually to ensure complete combustion with smaller packets of fuel and this may be considered a burden on the user in comparison to dealing with conventional stoves. The power variation with time is dependent on this attention. If perchance, the amount loaded at one time is more than what the system can combust fast, significant emissions will result. Here again it may turn out that a trained operator in a laboratory can get good emission performance, but users in the field may end up with poor emission performance.

In comparison to the above mentioned designs, gasifier stove with loaded fuel discussed in the earlier section provides a clearer alternative. Starting with the amount of cooking energy needed to cook one meal, the design of the stove has been 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

Table 4: Efficiency and emissions of various classes of stoves, [a] Reed et al and Phillips

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[a]	35 - 45	0.8 - 1.2	2 to 20
Optimized gasifier fan stove	40 to 50	0.8 - 1.0	2 to 9

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 which was indeed true.

11.6 Comparison with other studies

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 (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. Bhattacharya et al (2002) have presented the results of similar stoves from south east Asia and India. Still et al (2006) have 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. TLUD (top lit up-draft) stoves 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 4 and in Figure 14 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 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

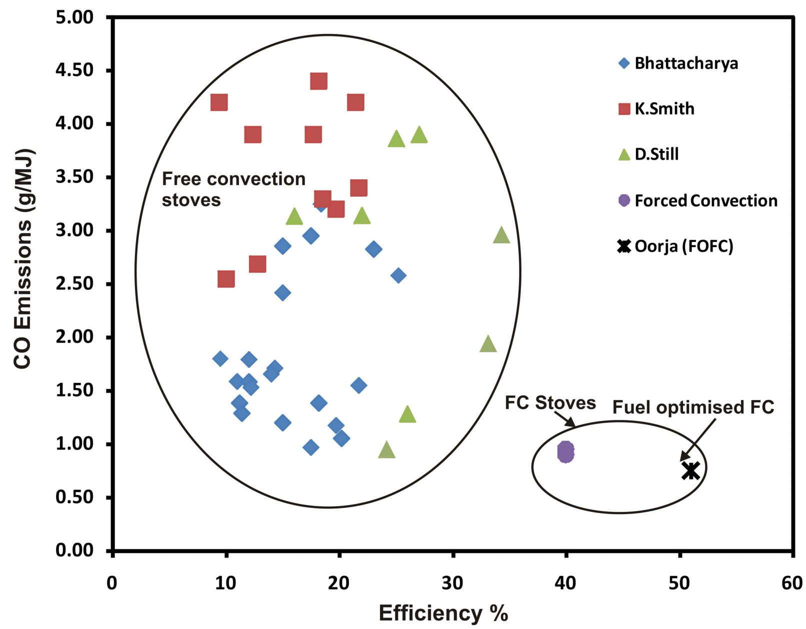

Figure 14: CO emissions (g/MJ) vs. water boiling efficiency from many studies

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 at undesirably short periods as in Phillips stove operation.

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, 1994). 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.

11.7 Larger power batch combustion systems

Due to issues of agro-residue shortage – largely, bagasse and groundnut shells the prices of pelleted 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. Coupled to this, BP, India got transformed into an Indian company, First Energy Private Limited, Pune (FEPL from now on) who sought sustainable markets for stoves and pellet fuels as the domestic market went down. They needed to expand into hospitality industry to provide advanced and appropriate solutions for cooking. This was to be achieved by keeping the essential fundamental ingredients much as in the early design using a different market strategy of owning up the combustion system with support for maintenance and replacement as needed but with a contract to buy a minimum amount of pellet fuel every month.

Scaling the small stove design for higher power levels was straightforward. Based on the subject discussed in section 11.2, The grate cross sectional area is obtained as $\dot{m}_{fuel}/FLF$, where FLF is the loading flux (kg per hour fuel per unit grate area) and so, the grate size is $\sqrt{\dot{m}_{fuel}/FLF}$. One can use a square combustion chamber as well and in this case, the cross section can also be sized equal to grate size. If the burn time has to be increased at a fixed power level, the combustion chamber depth is to be increased linearly.

If the particulate matter emission is to be significantly controlled, particularly, the $PM2.5$ level, then, one needs to use as low a FLF as possible. Thus, domestic combustion systems will have a fuel loading flux of about 100 kg/m^{2}h. Larger power systems will need to have a chimney to draw away the exhaust because one cannot introduce into the kitchen space so much of hot gas (at about 150 to 250°C). Thus particulate carry-over from the combustion system to the heat absorbing system (cooking vessel or such applications) itself will drop off some large particulate matter and additional material is allowed to go through a low velocity zone so that most large particulate matter is left behind. Thus, the particulate carry over issues can be dealt with. Use of higher FLF of about 200 to 250 kg/m^{2}h helps in achieving a more compact combustion system.

Systems with power levels of 0.75 kg/h (3 kWth) to 3 to 5 and 6 to 9 kg/h (12 to 36 kWth) were built, tested and marketed with much success in several metros – Bangalore, Hyderabad, Chennai, Coimbatore, and other places for hospitality applications. A total of 1500 tonnes per month of agro-residue pellets were being sold. Figure 15 shows one of the larger stoves working at about 6 kg/h. The flow inside the combustion chamber is more chaotic indicative of the role of turbulence. On left side is located

Figure 15: The 300 mm diameter, 5 to 8 kg/h industrial size combustion system burning pellets built by FEPL and marketed in several states in India

the power controller that allows the system to operate at low, medium and high power levels. Typical operational times are between 2 to 4 hours. For longer durations, two systems were provided and after the first one completed its fuel, the system would be replaced by a fresh one. This is one of the deficiencies of the batch operating system.

A system was built by FEPL for making what is known as dosas (thin pancakes) as can be seen in Fig. 16. The speciality of the design is the requirement of uniform temperature of 200 ± 10 °C over a wide pan. The combustion process heated a thermic fluid which circulated through the bottom of the large pan and maintained it at near-uniform temperature. It was a 3 to 5 kg/h pellet burning system. Since each system had a burn time of about two and half hours, two systems were provided and when the second one was functioning, the first one would cool down in about an hour and a half and would get loaded with fresh fuel. This approach was used to main continuous availability.

11.8 Bio-char from the batch combustion system

The method of operating the Oorja class stove in obtaining char is straightforward. During the operation, the flame front will move down igniting more and more fuel. This causes the mass loss largely due to the loss of volatiles. The mass loss rate drops to a low value as discussed later in section 13.2 associated with Fig. 36. The temperature of the fuel as also the grate over which the fuel rests will show ambient temperature till the flame arrives close to the grate. At this time, the temperature shoots up to 500 to 700°C. The temperature of the grate is tracked and when it suddenly shoots up to 500°C, the system is shut down. From the bottom, one can introduce nitrogen gas for a few minutes to cool down the char to less than 100°C and then extract the char. If there is no urgency, one can place ceramic wool blanket over the char and

Figure 16: Two 300 mm diameter combustion systems burning built by FEPL for the special application making dosas (thin pan cakes) on large scale using thermic fluid heater that maintains a temperature of 200 $\pm 10^{\circ}$ on the surface

allow the system to cool down. The amount of char obtained is about 30 $\pm$ 3 % of the sun-dry biomass.

11.9 Limitations of batch combustion systems

The Oorja class systems work extremely well when clean wood derived pellets are used. These have an ash of about a percent and therefore, leave little residue. Agro-residue pellets have an ash fraction of 8 $\pm$ 2 %. Experience in operating a large number of systems over a period of time showed that ash was in the form of fine powder most of time. In one season, though, a large number of issues of *ash fusion* got reported. Experiments done at the laboratory with the specific fuel also confirmed the issue of ash fusion. The subject of ash fusion was not quite new and even as of 1999, experimental systems were designed to test the ash fusion issues from specific residues at IISc (see CGPL, 2006) and many agricultural residues were indeed tested using an early development version of reverse down draft system. Tom Miles from National Renewable Energy Laboratory, USA and other colleagues (Miles, et al, 1996) had studied extensively the phenomenon in boilers in the USA. A significant effort into the subject had revealed that the presence of potassium and sodium oxides in the plant residues reduced the ash fusion temperature and caused deposits when the surrounding conditions allowed for it (like lower temperature boiler tubes and grate during cooling). Once the issues were understood, it was suggested to the FEPL marketing team that efforts be made to limit the problematic residues that turned out to be soybean waste from a specific source. When this was eliminated, the the problem was overcome.

Over a time, the major demand from the consumers was continuous combustion system so that they were not limited to a specific operational duration. This led to the development of clean continuous combustion systems to be discussed below.

12 Clean continuous combustion systems

12.1 The two types

In the following are described two different types of continuous biomass combustion devices – the horizontally and vertically arranged. And as the names suggest, combustion gets completed in the horizontal and vertical axes respectively. The former approach got introduced because of a special need discussed below in section 12.3 and the vertical mode is the more common arrangement used also in all the free convection based systems because gravity is the key feature of relevance there. In the case of forced convection systems, free convection effects will continue to play a role and given identical air flow arrangements, a vertically arranged combustion system will operate at a slightly larger power than horizontal combustion system.

On a different consideration, horizontal systems require less of vertical space and in the case of large systems, due to optimization of space requirements in small industries, the horizontal systems are considered more appropriate. Also the design of horizontal systems allows for the use of pellets and sized pieces of biomass more conveniently. Thus, both these system designs have relevance in practice and are used widely. It must be brought out that these are very novel and new designs not uncovered in earlier literature and so, many details of practical systems are also brought out in the following. One additional innovative design in which a grate with large inclination is used has also been developed. It has special advantages for certain classes of fuels like straws which require either complete combustion or char extraction.

12.2 Early ideas

The conceptualization of a continuous system that could retain gasification principles, at least in part needed much thinking because there seemed to be no effort in this direction in the earlier literature. During the evolution of the ideas, the first idea was to use a throat to enable the passage of volatiles through a bed of char. Figure 17 was the first one that was conceived. 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 enabled accessibility of the fuel feed port for introducing

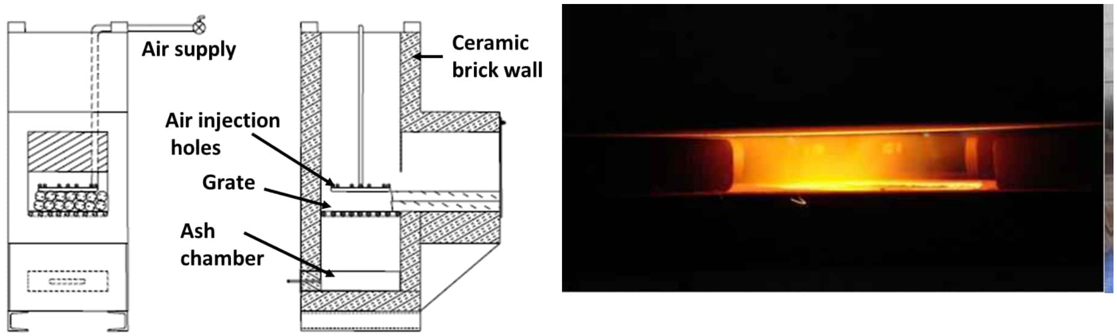

Figure 17: The ejector induced gasifier stove, EIGAS

fuel when needed. Air was introduced in the form of fine high velocity jets (velocities of 20 to 50 m/s) in a region over the grate (this needed blower with power demand of 12 to 24 We). The air jets were located about 100 to 200 mm away from the fuel bed. The ejector action caused suction in the zone below the air nozzles. This enabled air being drawn from the sides and the bottom region if the bottom of the grate region was open. This air drawn through the horizontal bed of fuel through an ejector action caused a flame front to propagate through the solid fuel and char bed much like in a gasification system when the fuel bed was lit. This process generated combustible volatiles that burnt in the vertical combustion chamber after being mixed with the high speed jets of air because of ejector action. The hot charcoal that moved onto the grate would 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 got created in the chamber for a "mild or flameless" combustion mode to dominate thereby ensuring the lowering of emissions (of CO and un-burnt hydrocarbons). These conditions got created because the air velocities were very high due to which the fuel gases - partially going through gasification, part volatiles mix intensely leading to complete combustion of the fuel. The disadvantage of the current system was the need for a higher power blower. Fortunately, the cheaper DC based blowers blowers of advanced type with the fan rotating at 6000 to 20000 rpm became available. Higher speeds allow for higher pressure $\sim$ 100 mm water gauge. This allowed the ejector action to be intense.

12.3 HC^{3}D

HC^{3}D, a horizontal continuous clean combustion device was first experimented upon aiming to replace diesel burner that was being used as a sand drier in a foundry. The

Figure 18: The first experiments with firewood and only a secondary air supply from a high speed blower in the horizontal mode

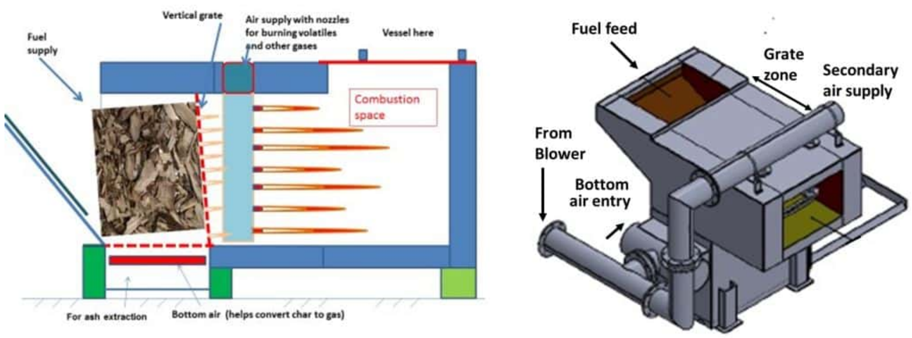

Figure 19: Depiction of the principles of the horizontal ejector based system also termed horizontal clean continuous combustion device, HC^3D

combustion behaviour appeared smooth and clean unobserved with other modes as seen in Fig. 18. The flame quality appeared so outstanding that after analysis, it was found that the jet velocities were about 50 m/s and created individual lifted flames that allowed premixing of volatiles and air and so, near complete combustion of the gases composed largely of volatiles. The design was such that the char had very little chance to convert and was left behind. In order to consume the charcoal as well, it was necessary to introduce a separate air - like primary air in REDS class systems. This was what was conceived next. The depiction of ideas (also discussed in some detail in Mukunda, 2015) and a 3-D rendering of the system are set out in Fig. 19.

The principal features remain the same as in the case of batch system. Air supply has two paths - one to the bottom of the bed ("bottom air" or "primary air") and second, downstream ("top air" or "secondary air"). In the bottom of the bed, the air

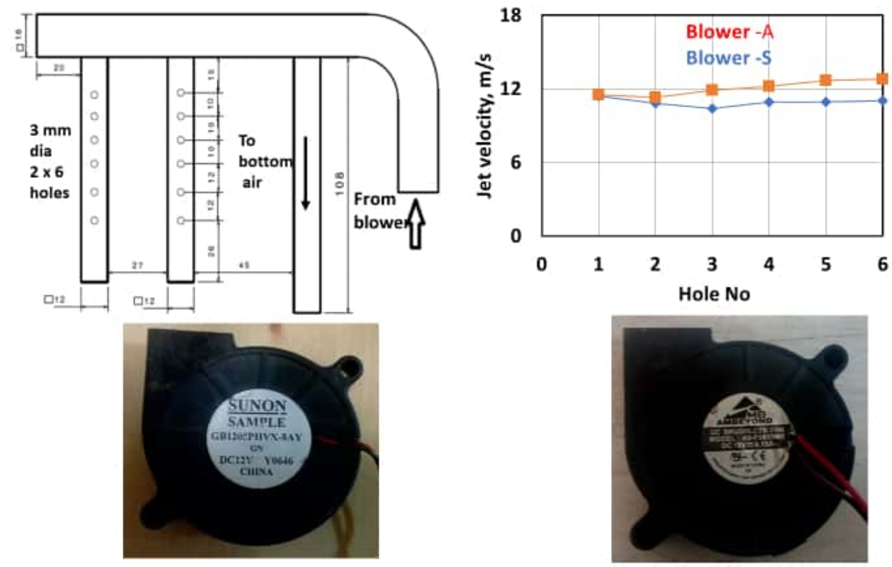

Figure 20: The air supply system used in continuous combustion systems

is introduced so that it enters the fuel bed above the grate nearly uniformly. The air supply systems for the continuous combustion systems are a crucial component of the system and are discussed now.

12.3.1 Air supply systems

In the case of batch operating system like Oorja (or REDS, TLUD), the air supply system is based on a 3.7 V battery driven fan at 1.2 to 1.5 W. Such fans got developed for cooling the components in a laptop computer in mid-nineties and got produced in large numbers and hence were inexpensive - one would get them at less than 3 USD per fan. These fans had to overcome the pressure drop across the packed fuel bed of 100 mm depth at very low flow rates at 0.4 lit/s (0.85 cfm). In the case of continuous systems, the issue is more difficult because the fuel rich gases are to be sucked out of a hot packed char bed over the grate with fuel also being fed continuously at the top. Since the gases are hot, the more appropriate way is to suck the gases by ejector action - an action where high speed air jets create suction behind them and this enables the fuel rich hot gases being drawn into the air stream for combustion. One can notice that in Fig. 18 what was used was a Wolf blower that operated at 10000 rpm and so allowed flow rates of 20 lit/s at more than 200 mm water gauge. And, the flow was introduced through air jets arranged on a strut. Therefore, it was thought important to look for blowers instead of fans for possible application to combustion systems of 1 kg/h biomass like in Oorja. After search in the market, it was found that smallest blower operating at speeds of 6300 to 6800 rpm and other two stage fans operating at fan speeds up to 18000 rpm were available. These were produced by a Taiwanese company called Sunon. The blowers operating at 3.7 V and speeds of 5000 rpm were found inadequate because they did not deliver the air at the minimum required pressure which was about 12 mm water gauge. Hence for the 1 kg/h combustion system, Sunon blower operating at 12 V and 2 W was chosen.

Typical air jet systems that were deployed are set out in Fig. 20. The air supply arrangement is shown in the top left figure. The blower is connected at the bottom to ensure that no hot air flow comes along this path when the blower is switched off. The air goes along the top line and a part of it goes to the bottom region to be connected the zone below the grate. The other part is delivered to two struts with 6 holes each of 3 mm diameter. The total air flow delivered is about 1 gm/s and about 60 to 70 % goes to secondary air jet and the remaining to the primary or bottom air. Two small blowers - Sunon and Ambeyond procured from in the market (also shown in the figure) were tested and both operated at 6300 to 6500 rpm and performed well with jet speeds shown in the top right of Fig. 20. The arrangement of the struts is such that they are in the path of flow of gases and is satisfactory for small systems. However, for larger power systems, it is advantageous to locate the struts at the edge so that the metal tubes do not intersect the hot gases directly. In these cases, the jets are at an angle of 45 degrees all around that so that the ejector action directs the fluid outwards from the fuel supply side. In vertically oriented systems, one can also use this idea as can be seen in section 12.5 and more specifically, Fig. 31. This will improve the life of the struts. For higher power level systems like 3 to 4 kg/h, two stage fans at 12 V, 12 W are adequate. There are other more powerful blowers drawing power up to 24 and 36 W. These can be used in combustion systems up to 12 kg/h. Beyond this, one can use centrifugal blowers or ring blowers depending on the design requirement for 110/230 V AC systems. The jet speeds in all the higher power systems is 20 to 50 m/s.

12.3.2 HC^{3}D - the combustion behaviour

When the fuel bed is ignited, the initial functioning is much like in a batch mode system. The flame over the top of the bed propagates towards the grate and the biomass gets converted to char. Subsequently, the char also oxidizes and the gases go through the bed above and enter the combustion chamber where they are fully burnt with the secondary air. Since the jet velocities are high, the flame acquire a lifted flame configuration with premixing of the fuel rich gases and air that occurs before the mixture gets burnt up.

Fuel in terms of pieces smaller in size compared to the size of the fuel port (10 to 20 mm for a 1.5 kg/h domestic stove and larger sizes for larger systems) is fed periodically. The initial feed of about a third in height of the combustion zone is placed on the grate and lit using a small amount of of kerosene, alcohol or a Gel fuel without the fan being switched on. This is because the air currents cause delayed ignition process. In the steady combustion, two types of processes occur. The first type relates to the char that rests on the grate being converted to producer gas before entry into the combustion chamber because of the entrainment process. The second part relates to the top of the bed that has some biomass that also release volatiles. These volatiles and some air being drawn from the ambient through the fuel port get partly mixed and enter the combustion chamber directly due to air induction and burn up in the combustion zone. In view of the combined processes, the total process can be termed quasi-gasification process. The secondary air jets lead to induction of fuel rich gases such that a significant part of the un-burnt gases from the fuel zone get mixed with the air before final combustion occurs much like in a flameless combustion system (Kumar et al, 2002).

Full air supply can be turned on a few minutes after ignition. Then, the top of the fuel bed releases volatiles and these burn up in the combustion space downstream after mixing with the ejector air that is introduced at speeds of 10 m/s or more through 3 to 4 mm diameter holes. After about ten minutes during which period the fuel bed generates char over the grate, more fuel can be fed into the fuel space - to fill up the entire space. Allowing a small amount of space near the lip of the fuel port will permit a small amount of air induction. This artifice enables biomass fuels with varying CHNO composition to be burnt in a clean manner. The system will take 10 to 15 mins from ignition time to attain a steady combustion process.

12.3.3 Single pan and two-pan systems

Much development effort went into both single pan and two-pan combustion systems. During the development of single pan system, inputs from field indicated that most families cooked on a regular basis at least two supportive foods - rice and rasam, a vegetable filled soup or rotis and spice filled boiled vegetable mix. It was considered desirable to cook them simultaneously to reduce the time of cooking. This needed two cooking pot areas. This was how the two-pan combustion system became relevant. Also, the cost of two separate single pan systems and a single two-pan system would favour the latter, because the single combustion system served two pans at about 20 % higher burn rate (and so, a reduction in amount of fuel used when we need to cook different foods). It was thought that the neatest way of handling two pans was to mount two vessels in a common combustion space. Over a time, it turned out that even a single pan system would have value. Thus, considerable effort was made in researching designs, materials and air support systems over a period of time. It was

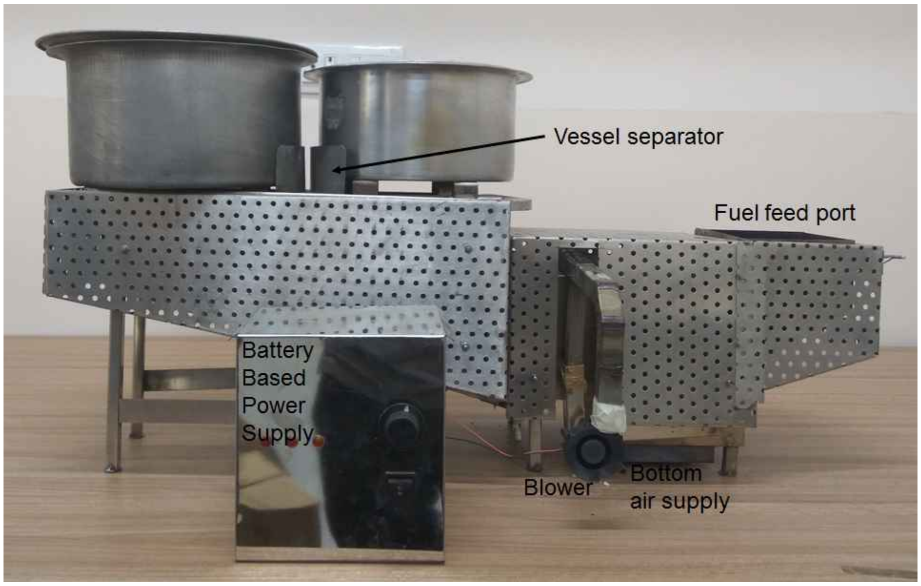

Figure 21: The two-pan horizontal continuous clean combustion device (HC^{3}D) for domestic use - 1.2 kg/h with a 12 V DC, 2 W Sunon blower operated with a rechargeable battery

also important to engineer the product for aesthetics because individuals wishing to own a system for their homes are very particular of aesthetics in comparison to industrial houses where functionality is given higher importance. Thus several versions of basic designs and power packs were explored.

One system is shown in Fig. 21 that shows all the features. As discussed earlier, the blower is the 12 V DC, 2 W, 6300 rpm Sunon make. The combustion was indeed outstanding.

Figure 22 shows two different two pan designs with the right one showing water filled aluminium vessels placed over the combustion system. The lower part of the figure shows the time slices of the flame coming off the struts drawn from a video of the flame. What can be noted is that flame comes out of the individual struts and merges together. The flame temperature at the edge of the luminous zone is 1050 to 1150°C.

A simple and useful application for water heating is shown in Fig. 23. A specially designed container with five different ducts welded to the vessel containing the water is placed on the space where hot gases emerge. Once the combustion system is started, it takes approximately 20 minutes before hot water at temperatures of 40 to 45°C becomes available. The fuel shown in the figure is cut wood pieces. It can easily accept

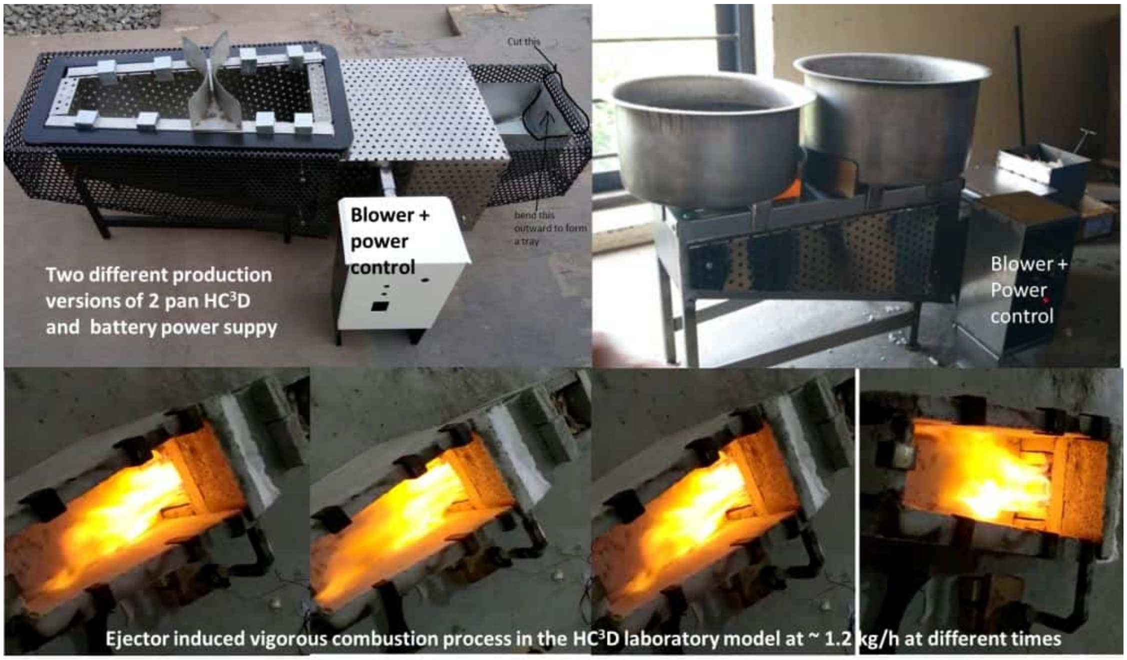

Figure 22: The two-pan horizontal continuous clean combustion device (HC3D) for domestic use - 1.2 kg/h with a 2 W blower operated with a rechargeable battery. Flame pictures coming off the the air nozzles at four different instants of time

tree droppings of small branches cut into small pieces and other similar garden waste as well.

The design has been realized at several throughputs - 0.8 to 1.2 kg/h, 2.5 to 4 kg/h, 6 to 10 kg/h and beyond that up to 200 kg/h with the same general principles. The smaller size systems up to 15 kg/h can be realized with DC Sunon blower/two-stage fans and beyond that with AC centrifugal blowers. As indicated earlier, the key parameter that governs the design is the allowable fuel loading flux, FLF (kg/m^{2}h) and for domestic applications, the flux must be set at the lowest (100 to 120 kg/m^{2}h) and for industrial applications in which the hot gas path has opportunity to dump some particulate matter in other zones and allow for a clean exhaust, one can choose larger flux values, up to 250 kg/m^{2}h. In one instance, the design for 20 kg/h hardware also delivered 35 kg/h of pellet fuel with increased total flow rate (both the primary and secondary flow rates).

The above design can accept all the fuels shown in Fig. 3 in section 4. As can be noted from the figure, the packing densities of fuels that can be handled is very wide - from 100 kg/m^3 to 700 kg/m^3. While operational performance has been checked for

Figure 23: Water heating arrangement mounted on a 1.2 kg/h combustion system to deliver hot water

all the fuels, select tests on efficiency and emission performance have been performed on 10 % dry cut pieces of casuarina firewood.

It has been tested with pellet fuels as well. In this case, the pellet fuel was produced from agricultural residues with an ash content of 8.5 %. The Sunon fan, 40 mm x 40 mm x 56 mm used here operated on 12 V, 12 W DC power supply at 15000 rpm and delivered air of 30 m^3/h of air at 40 mm water gauge. The quality of combustion in these systems is outstanding as can be seen in Fig. 24.

12.4 Larger HC^{3}D field level systems

The 2.5 to 4 kg/h system described in Fig. 24 has been used for larger cooking applications. Figure 25 shows the field level deployment. In this particular application, the fuel was cashew shell waste resulting from roasting process of the cashew nut. The shells have some residual oil and hence have a calorific value larger than wood by 15 to 20 %. This became clear when the system that worked on wood chips. It ran fuel rich. To deal with this problem, the secondary hole diameter was increased by 10 %. This normalised the combustion process. It was used in a kitchen close to cashew processing area for preparing food (in this case, idlis - steam cooking rice cake).

To appreciate the importance of FLF, it is useful to calculate the sizes for typical consumption rates. Semi-industrial demands of biomass combustion systems have

Figure 24: The single pan HC^{3}D at 2.5 to 4 kg/h with a 12 V, 12 W two-stage fan operated with a rechargeable battery burning pellet fuel

Figure 25: The single pan HC3D at about 4 kg/h with a 12 V, 12 W two-stage fan operated with a rechargeable battery burning cashew shell fuel

been estimated to be around 20 to 200 kg/h. A 50 kg/h system designed with 100 kg/m^{2}h of FLF will have grate zone dimensions of 0.7 m x 0.7 m x 0.7 m and designed with 200 kg/m^{2}h of FLF will have dimensions of 0.5 m x 0.5 m x 0.5 m. Thus, the fuel loading flux is a key parameter for design. The air flow rate bears stoichiometric proportions and should be 7 times the demanded fuel burn rate. It is split between the primary and secondary in a ratio of 0.2:0.8 to 0.5:0.5. For charcoal producing combustion systems, the primary air is kept low so that char is left behind and can be extracted at a suitable time during the operation when the grate area gets loaded with char.

Three applications amongst six working systems are set out here. A 12 kg/h system was built for a deep frying semi-industrial establishment is shown in Fig. 26. The hot gases are delivered via a channel so that the gases directly impact the bottom of the khadai (pan). This was important since an alternate design that allowed the combustion gases to come laterally on to the pan bottom side did not perform as well in comparison to diesel fired burner. The major issue was that the time required for oil to regain the temperature after withdrawing fried material before the next batch was introduced was 90 s in diesel-fired system and but 180 s in the pellet fired system.

The change involving directing the flow of hot gases to the bottom of the pan helped bring down the time to between 90 to 100 s and hence was considered acceptable. An evaluation showed that 2.5 kg pellets were adequate instead of a kg diesel. While the energy equivalence ratio would imply 4 kg pellets for every kg of diesel, the above result implied that the diesel system must have been operated very inefficiently. In any case, the pellet alternative was economically far superior to diesel.

The left side inset of Fig. 26 shows the cut-away section of the arrangement. The gases exiting the pan area were at 250°C and in the first set of operations, showed exhaust with emissions of $PM10$ beyond acceptable limits. This required a special engineering of the bottom region of the exhaust in which the gases entered tangentially into a region at the centre of which the vertical exhaust pipe was located. This created a cyclone like arrangement and it turned out that the particulate emission fell much below the norm and the issue was resolved.

Figure 27 refers to the combustion system working at 20 kg/h on a vapour absorption chiller unit at a major industry. It was intended to replace 5 liters per hour of diesel. The interiors were made of special high temperature fire bricks as the expectation of reliability of performance for long durations was a necessary criterion for acceptance of this system. The system was operated for hundred continuous hours and test results showed that they matched with those from the diesel operated system. Subsequently, it was operated for 1000 test hours as well. The combustion system did not show any issues during this period.

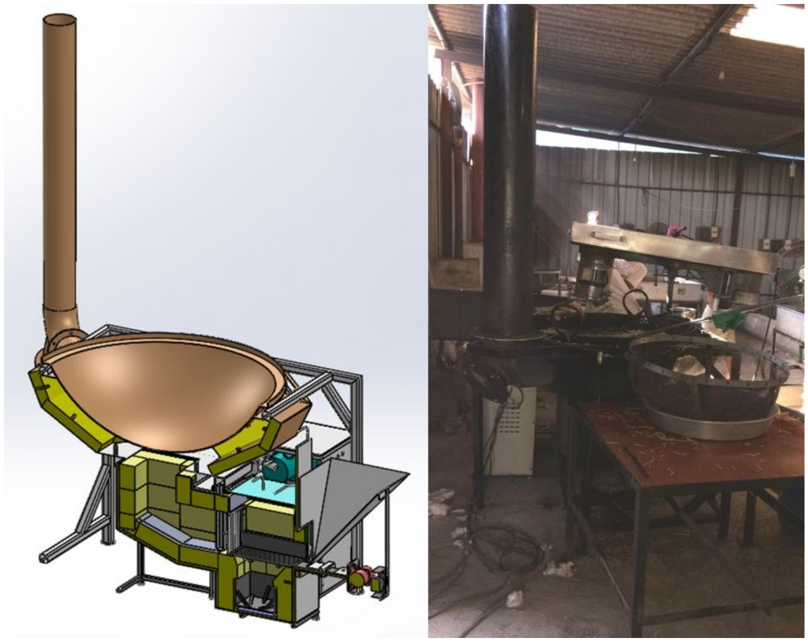

Figure 26: The deep frying single pan application using pellet burning 12 kg/h HC^{3}D system with chimney using a 230 V centrifugal blower

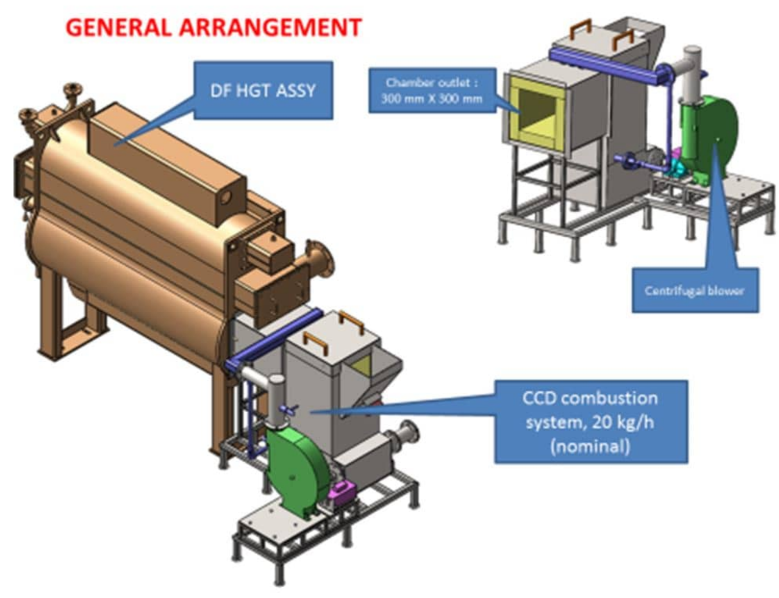

Figure 27: The industrial testing of a vapour absorption refrigerator system replacing oil combustion system by a pellet burning 20 kg/h HC^{3}D system

Figure 28: The HC^{3}D system with chimney operating at about 50 kg/h with wood cuts from a furniture industry in a blackening unit for metal parts

Another project developed for a small scale industry was related to steel component blackening. This demanded that a large body of water with dissolved chemicals be maintained near boiling point and the plant be operated for 8 to 16 hours a day. The outer civil engineering construction has a metal container in which the solution was kept. The space between the metal container and the civil construction was sealed at the top and the annular space allowed the passage of hot gases. The gases after having delivered the heat to the metal container would be led to a tall chimney. The industry was located in a such a way that the chimney went up two floors before the gases were exhausted into the atmosphere. Figure 28 shows the system with the inset on the right showing the exhaust. Since the application was one of average heat absorption into a large system, changes in the power delivered would not be important. Once the liquid had reached the near-boiling condition, the amount of heat required would not be as large as getting the entire liquid to that condition. This aspect was so significant that there were occasions when there was power failure and the system operated just as well without the blower operating. Also, the exhaust which was at around 175°C was very clean. This system has been operating for over an year at the time of writing.

Figure 29 presents a potato chip making unit that is operated using a 50 kg/h system. The fuel wood used is off-cuts from a wood processing industry. The amount of cooking oil used is 250 liters that to be taken to 200°C before potato chip frying operation began. The hot gases from the secondary jets go around the tank till the

Figure 29: The HC^{3}D at about 50 kg/h with wood cuts from a wood processing industry for potato chip deep frying; the off-cuts used in the combustion system are clearly visible

end and then to a chimney located outside the building. Inadequacies of operation in early times were traced to the use of wet biomass. And it was shown that once dried biomass was used, the performance was as good as that from diesel in terms of the output.

For puffed rice making, a special combustion system of 200 kg/h using furniture industry wastes of all sizes was built and is shown in Fig. 30. The top left part of the figure shows the elements of the system. The rotating roaster was housed inside a room and at one end of this, a tall chimney was provided. The combustion system delivered hot gases to the rotating roaster to heat up the outer surface to 250 to 275°C to enable the pre-processed paddy to be heated and allowed to puff. The puffed material would be collected at the end of the roaster. The roasting process was helped using sand that recirculated inside except for small part that exited from the system.

The speciality of the combustion system was to meet the requirement of using furniture waste containing a range of sizes and shapes, a combination of wastes shown in Fig. 2 in section 4. The solid wastes contained such a range of sizes that some would burn up very fast and others took a longer time. Even with a travelling grate that was designed for this, it turned out about 10 % of the material would fall into the ash collection chamber of the HC^{3}D system and would produce volatiles. This issue was solved by delivering the the largely converted fuel containing ash and yet-to-be-

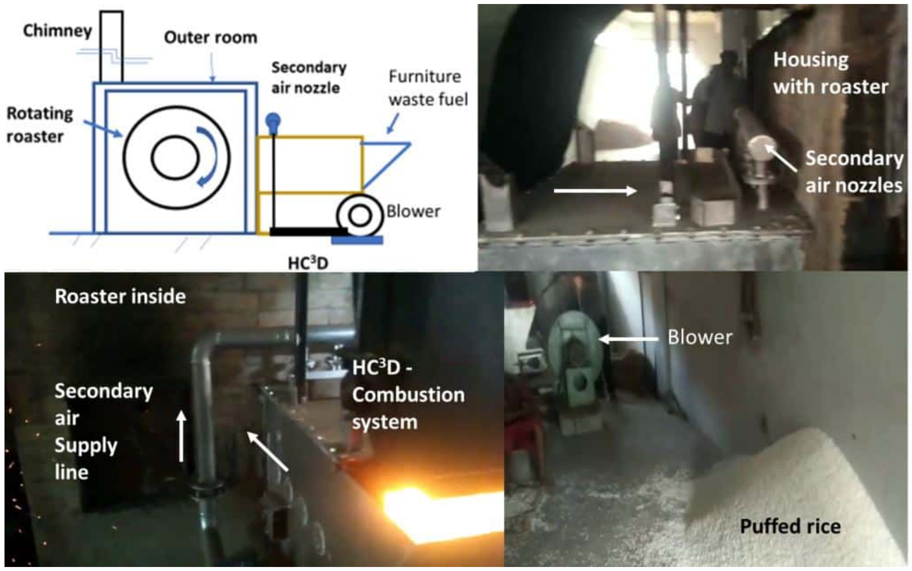

Figure 30: Puffed rice producing roaster operating with HC^{3}D system on fuurniture waste fuel with travelling grate

oxidized carbon into the chamber/room itself. The mean velocities inside the room were small and air was available for oxidizing the un-burnt char over longer periods of time. The gases that delivered the heat were extracted away in the chimney at one end of the room. The emissions from this chimney were clean enough to meet the local emission standards; The technical issues of this problem were the most difficult to resolve.

There are more than ten other installations at biomass consumption rates of 5 to 100 kg/h functioning for cooking, roasting and deep frying applications.

12.5 VEBCOD

The vertical ejector biomass combustion device (VEBCOD) at 1 kg/h is shown in Fig. 31. This design is similar to the HC^{3}D design. The primary air is delivered to the space below the grate and the secondary air through a square tube arranged to be located in the brickwork above the fuel supply zone. Locating the square tube within the brickwork helps in longer life of the tubes since the metal tubes do not intersect the combustion gases directly. It has holes drilled an an angle so that the vertical component of the momentum helps in the ejector action. The design benefits also from some free convection component of the flow to avoid pressure drop due to the horizontal component of the air jets. It is based on 12 V, 2 W Sunon blower that delivers

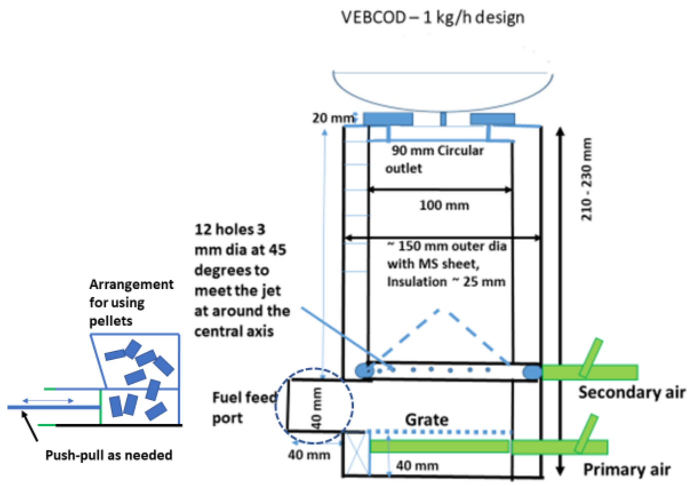

Figure 31: The basic features of a Vertical ejector biomass combustion device

both primary and the secondary air. The fuel feed port is 40 mm x 80 mm and accepts firewood of a maximum size of about 20 mm. If larger sizes wood pieces are loaded, the effective burning surface area comes down and power level drops. A combination of smaller sizes ($\sim$ 15 mm) and larger sizes (up to 25 mm) would also be a good choice to get the desired thermal output. The key in getting higher quality combustion is to provide an exit smaller in size compared to the chamber size. In the figure is shown a 90 mm circular exit dimension. What this does is to create recirculation zones for the flow going up helping better combustion. While the combustion process is not as steady as in Oorja class system and the measured flame temperatures fluctua between 1200 and 1300 K, this feature is limited to 1 kg/h design because the ejector action is limited by the velocities of 9 to 11 m/s and the up-draft because of free convection leads to fuel burn rate about a few percent higher. The left side of Fig. 31 shows the details of the design that allows the use of pellet fuels in VEBCOD. This can be treated as an idea at present and no hardware has actually been built using this idea because there was no specific requirement.

The system for firewood was built by two licensees with slightly different aesthetic appearances shown in Fig. 32. The early systems were simplified by eliminating the valves and any power control was expected to be exercised by adding or withdrawing firewood.

Figure 33 shows the arrangement for the deployment of four different combustion systems with two of 3 to 6 kg/h systems and two of 6 to 10 kg/h systems using a single large blower whose flow rate was designed at an effective 15 kg/h operation. The

Figure 32: The 1 kg/h VEBCOD using 12 V, 2 W Sunon blower- test version and production versions

Figure 33: Two of 3 to 6 kg/h, two of 6 to 10 kg/h VEBCOD systems operating with a single blower for community cooking

system had initial issues in terms of arrangement, but overcome when the systematic arrangements were executed. It is operated for about six hours in the morning and and four hours towards the evening.

Figure 34 shows the a frying pan on the 6 kg/h system and a 15 kg/h system delivering heat to concentrate weak natural brown sugar solution into brown sugar cubes (jaggery as it is called locally). The speciality of this design is that the vessel was very wide and the delivered heat needed to be as uniform as possible. This was achieved by adding an additional heat transfer resistance to the central area. The combustion system was set on rails so that it could be moved in or out as needed for

Figure 34: 3 to 6 kg/h for larger cooking and 15 - 20 kg/h VEBCOD operating system for brown sugar production

use towards the end for taking the syrup to moulds for producing brown sugar cubes.

13 Efficiency and emissions

13.1 Efficiency or Flame temperature as performance indicator

Whenever it comes to domestic stoves, water boiling efficiency has been chosen as the criterion to identify better stoves, classically called improved cook stoves. The question being brought up here is whether such an approach that has been adopted World-over for over five decades is indeed correct. The issue arises because the utilization efficiency is the combined effect of combustion efficiency and heat transfer efficiency. In order to combine these two for the purposes of standardization, flat bottom vessels of specific sizes are prescribed for tests at specific power levels. Such an approach seems to be based on a consideration that combustion technology changes if at all, only moderately because most combustion approaches were free convective based till the last decade. The combustion efficiency of such systems has been known to be poor and energy balance studies show that unaccounted losses are about 30 % (Sharma, 1993). These unaccounted losses are essentially due to incomplete combustion caused by large scale free convective effects (Varun, 2012). However, properly designed forced convection system can increase the efficiency by a factor of 1.5 or more and hence, one can deliver more power for cooking. *Larger cooking pots can be served with these devices at the same fuel consumption rate.*

If one were to look at combustion devices in gas turbine engines for instance, while combustion efficiency is still retained as one criterion for performance, a more appropriate one that affects the performance of the system is the temperature distribution at the exit of the combustor. This indicates to the possibility of separating the combustion efficiency from heat transfer efficiency.

However, in the case of domestic combustion systems, in view of wide dependence on water boiling efficiencies in practice, studies are made towards obtaining these values even if their implementation for dissemination has not had much impact. In the case of larger size systems, one needs to use a chimney to let out hot gases (at 150 to 250°C) to prevent them from being led into the working space. Of course, these emissions should also obey the industrial norms of pollution control of the corresponding Government or administration. Select installations have been studied for this purpose.

13.2 Oorja – Efficiency and emissions

Before release of the stove for developments involving engineering and production, emission measurements carried out at fuel consumption rates of 0.72 and 0.54 kg/h 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 35 shows the variation of the volumetric ratio of CO-to-CO_2 with time of operation. The first phase - flaming mode shows a 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 (Smith et al, 2000). There are also test-to-test variations in the CO emissions. These are largely because of the differences in the packing of the pellets in the bed. The overall $CO:CO_2$ was found as 0.01 (volumetric) even though char burn alone creates far more CO. These meet the requirements of the Indian standards and hence, considered acceptable.

The development was carried out over a period with different fuels, different sized combustion chambers and designs of air supply to establish the performance as a function of various parameters on efficiency. Actual emission measurements were undertaken in the last stage as it was clear that obtaining the highest combustion efficiency (and accompanying utilization efficiency) with relatively short visible flame heights was needed to be achieved first; it was inferred that this would also imply reducing the emissions. The amount of secondary air was varied to obtain a short visible flame.

The relevant dimensions of the stoves built for this purpose and their performance are presented in Table 5. The experiments were made with the stove and vessel with water kept on a balance. The mass of the system was continuously measured along with the temperature of the water after it was vigorously stirred once in a while.

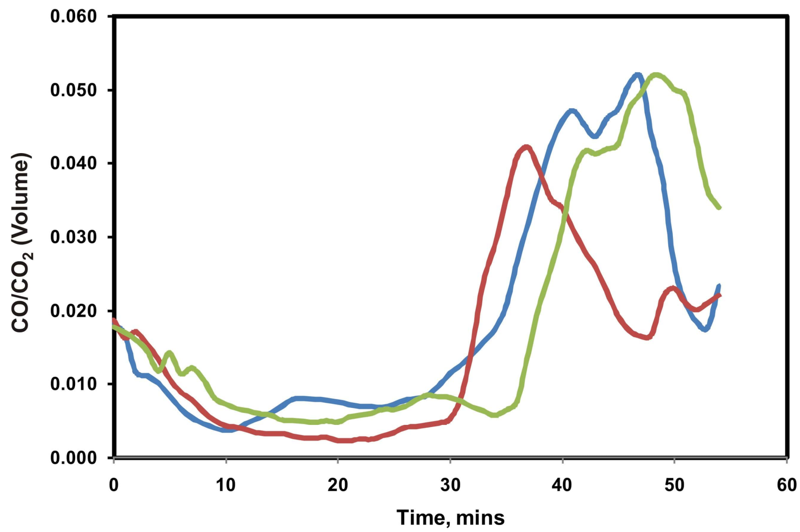

Figure 35: The variation of the volumetric ratio of CO to CO_2 during a stove operation. The operation till 30 mins is in flaming mode; char mode operation begins after a short transition

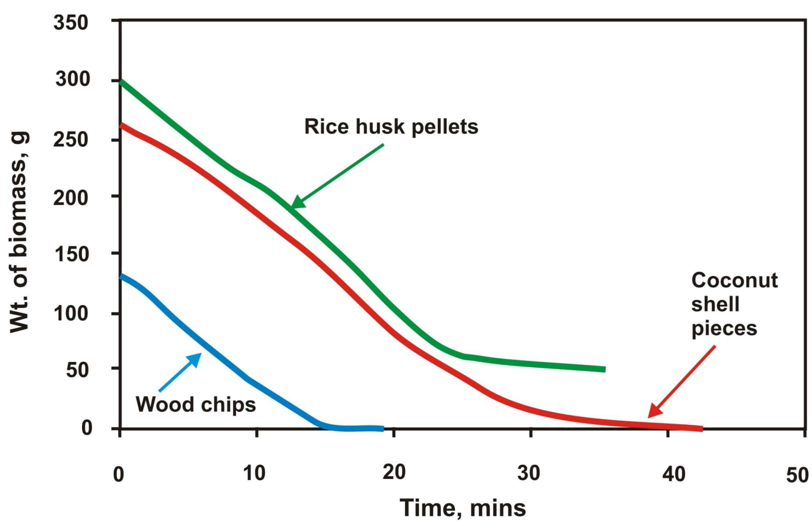

Figure 36: The mass of the fuel with time during the stove efficiency tests. The slope of the curve gives the mass loss rate

Table 5: Initial 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, η_{wb} = Water boiling efficiency

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
Stove dia. = 125 mm, chamber volume = 0.9 liter, Vessel = 10 liter							
WC	200	10	0.8	170	30 + 8	5.0	48.0
MP + WC	366	14	10.0	325 + 25	40 + 11	3.5	51.5

Figure 36 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 power output during the second phase 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.

Three cooking vessels were used for determination of the thermal utilization efficiency. The consideration behind this choice is that small families may use smaller vessels and larger families, larger vessels. It was considered valuable to determine the efficiency with vessel size. It can be expected that larger diameter vessels extract more heat compared to smaller vessels and hence designs that allow greater heat extraction from the same stove would be the appropriate choice. The cooking vessels were aluminium vessels of 10 liter volume (diameter of 320 mm, height of 160 mm, and 0.96 kg weight), 6 liter volume (diameter of 260 mm, height of 130 mm and 0.61 kg weight) and 2.5 liter volume (diameter of 205 mm, height of 105 mm and 0.34 kg weight).

The lighting up process used two approaches. The first one used about 15 ml of kerosene on the top region of the fuel bed and the second one used about 25 g of fine wood chips over which about 10 ml of kerosene was doused. The kerosene soaked fuel was lit with a match stick and the primary air was turned on. After a two minutes of vigorous combustion, the secondary air was turned on. The vessel containing water was kept just about a minute after the lighting. The procedure used in the tests was based on Indian standard specifications except that the tests were done with vessels larger than indicated in the specifications; the vessel diameters and volumes of water to be taken for the tests at various power levels were set in the 1991 specifications of

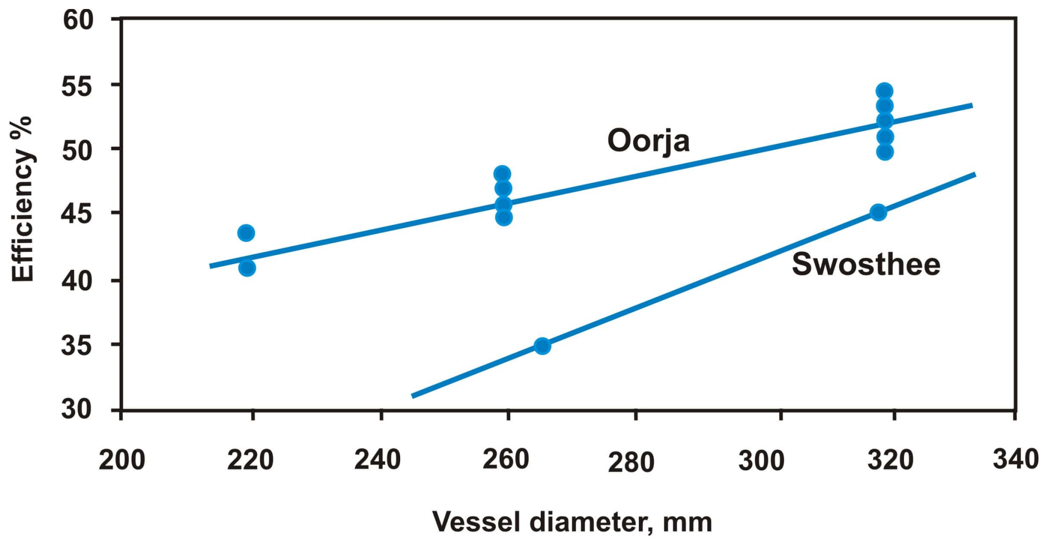

Figure 37: The effect of vessel diameter on efficiency, the lower plot is for the stove named Swosthee (Mukunda, et al, 1988)

the Bureau of Indian Standards keeping in mind lower efficiencies that were expected in the better of the stoves at that time. The currently achieved efficiencies are nearly double of those in earlier times; this is the reason for the choice of larger vessel sizes in the current tests.

The results of efficiency measurements can be noted from Table 5. The efficiency values are close to 50 % in most cases. The results on vessel diameter effect with the 100 mm dia stove are also shown in Figure 37. 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 (1988) albiet with lower efficiencies with a free convection based stove named "Swosthee" (for Single pan WOod SToves of High EfficiEncy) that is similar in configuration and performance to the currently prevalent rocket stove.

In more recent times, a stove called mimi moto has been produced and marketed as the "only mass-produced biomass stove to reach highest efficiency and emissions rating (ISO/IWA Tier 4)". Its introduction in Africa at a small scale (about 115 participants) through an entrepreneurial approach has been evaluated by Champion and Grieshop (2019) in Rwanda and Lambe et al (2020) in Kenya. The broad conclusions are that (a) the poor cannot afford to purchase the stove and (b) the option of use of wood as well as pellets has led to the use of wood with only marginal overall benefits and the inadequacy in service causes larger scale disillusionment. Some of these con-

Figure 38: Comparison between the flames behavior of a free convection stove and the single pan forced convection single pan HC^3D)

clusions are very similar to the Indian experience discussed in Mukunda et al (2010) where more than 400,000 stoves were marketed and pellet availability was ensured for more than 2 years. This work has been ignored while launching the stoves in Africa and the researchers who studied the value of the introduction seem to be unaware of the work in India. Clearly, scaling up the diffusion of new technologies has a wide spectrum of issues and not learning from others' experience is not a virtue.

13.3 HC^3D – efficiency and emissions

In order to obtain a comparison of the combustion behaviour between free convection and fan based continuous combustion systems, experiments were conducted on stoves of similar power. The combustion systems and the flame behaviour are set out in Fig. 38. One can notice that the flame size is much larger in the case of free convection stove (left picture) and forced convection combustion system (HC^3D, the right side picture). The variations of mass with time for the corresponding cases is set out in Fig. 39.

Figure 40 shows the variation of flame temperature at the top of the combustion system. As can be noted, HC^3D demonstrates a near uniform temperature of 1050 $\pm$ 50°C whereas free convective stove shows fluctuating temperatures between 800 $\pm$ 100°C. The drop in temperature after 50 minutes with HC3D stove is due to the consumption of 1 kg of the biomass fed. As can be noted in Figure 39, the mass has dropped to about 80 gms constituting the final char that takes time to get converted

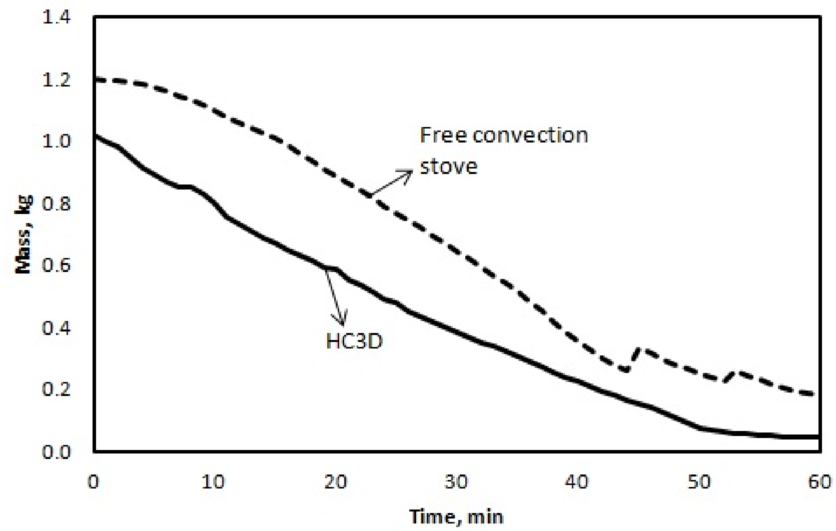

Figure 39: Comparison of mass loss vs time between a forced convection stove (HC3D) and a free convection based stove in the market

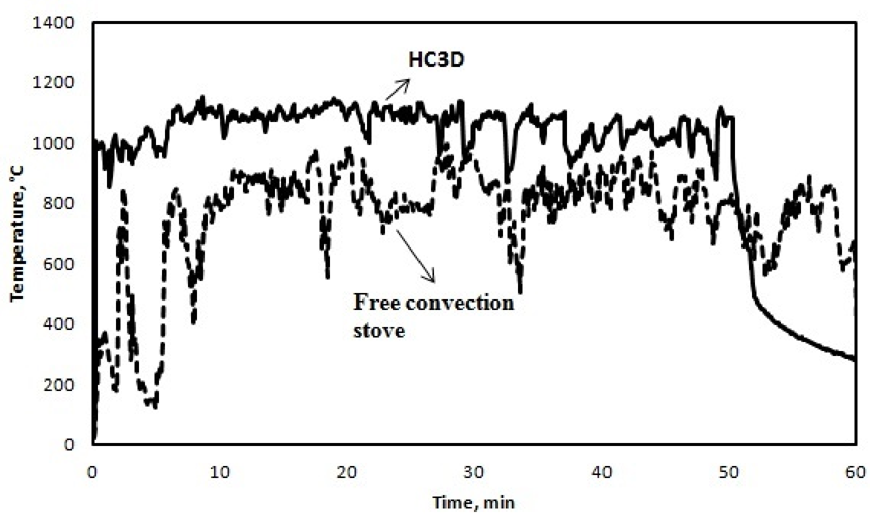

Figure 40: Comparison of flame temperatures between a forced convection stove (HC^3D) and a free convection based stove in the market

due to relatively inferior aero-thermal environment. In the case of free convection stove this situation is caused some time later.

The difference in the thermal performance between the two cases is due to the fact that fuel generation and air supply are near uniform in HC^3D, but widely varying temporally in the free convective stove. As discussed earlier, these lead to spatial and temporal variation of air-to-fuel ratio and the coupled volatilization variation due to fluctuating heat feed back.

The vessel size dependence on the utilization efficiency has been brought out in Mukunda et al (2010) in which the efficiency improves by 10 % if the diameter of the flat bottomed vessel increases from 220 mm to 300 mm. The results of efficiency measurements were made in a water boiling tests were made for 1 kg/h system with Aluminium vessel of a 6 liter, 270 mm dia vessel using a conventional procedure. Similar tests were conducted for two-pan stove at 1.5 kg/h with Aluminium vessels of 220 and 240 mm diameter. Efficiencies of 35 to 38 % have been measured for both these systems.

Based on all these observations, it appears that combustion efficiency and heat transfer efficiency can be decoupled also noting the fact that the use of the combustion system can be for cooking with a variety of shapes and diameters of vessels depending on the local culture and practise.

Emission measurements of CO, CO_2, and NO_x have been made by using a hood arrangement and a flue gas analyzer (FGA 53X Indus system). Figure 41 shows the test arrangements used for obtaining the CO and $PM2.5$ data from water boiling experiments lasting about an hour on the 2-pan HC^3D system.The left side shows the hood under which the two pans would be kept. After a number of experiments with the hood, it was uncovered that to get better estimates of the data, it was useful to reduce the dilution of the hot gases to get lower levels of oxygen in the measured stream and hence better estimates of CO_2 fraction.

For obtaining indoor air quality data, spot mounted instruments were used to make measurements of ambient CO and PM (The instrument for PM measurements is the Optical sensor based Airveda make with $PM2.5$ of 0 to 999 μg/m^3 and $PM10$ of 0 - 1999 μg/m^3 with relative errors of $\pm$ 10 % and $\pm$ 10 μg/m^3). The figure (Fig. 41) shows the two instruments mounted about 350 mm above the pans on the 2-pan stove to simulate the possible situation of a cook standing close to the pan for cooking operations. This distance is also appropriate for a cook sitting on the floor with stove in front for cooking. If the level of cook is lower than or at the same level as the pan, the cook will experience lower amounts of emissions in quiescent conditions. The tests conducted included one hour of operation of the combustion system with pans with background state of the emissions much before and after the stove operation.

Figure 41: The arrangement for the measurement of emissions. The hood on the left side used for obtaining the stove emissions and on the right meant for obtaining indoor air quality - CO and $PM2.5$

Complete combustion was assessed through the measurements of temperature and oxygen in the direct exhaust stream. These showed values of temperature between 900 to 1100°C and oxygen fraction between 4 to 6 % in various experiments performed to clear the stove for other measurements. The measurements using hood needed care in obtaining good estimates of the emissions.

The results of experiments on 1.5 kg/h two-pan stove that was run for one hour are as follows. Mass ratio, CO_2: biomass was obtained as 1.75 $\pm$ 0.05. Measurement of CO gave CO:CO_2 mass ratio as 0.006 $\pm$ 0.0015. This result can be expressed in other terms as well. CO produced in burning 1.5 kg in one hour can be expressed as 1500 x 1.75 x 0.006 g = 15.75 g; it works out to 262 mg/min; it can also be expressed as 0.6 g/MJ of fuel energy. This results is correct to within 25 %. Measurements of CO in the ambient cooking zone are set out in section 16 to follow.

The total particulate matter obtained from the difference in weight of the fine filter material as 22 $\pm$ 3 mg. This is is 15 mg/kg fuel or 0.36 mg/min or 1 mg/MJ.

The scale independent values are CO:CO_2 ratio, mg/MJ data and not the values in terms of emission per minute because this depends on the capacity of the stove (kg/h of burn rate). This is brought up specially because the recent trends in WHO guidelines (WHO, 2014) indicate to permitted emissions of CO and PM2.5 in terms of mg/min based on assumptions on air exchange rates in a standard kitchen. The essential problem with these guidelines is that the magnitudes limit indirectly the power rating of the stoves even for the low emitting stoves. The power level at which the emissions can be met with will be one 0.65 kg/h stove. Family cooking in India occurs for an average of 5 members and needs two single pan stoves of 650 to 750 g/h or two-pan stove of 1.5 kg/h for about an hour twice daily. This situation may not be universal but sufficiently general.

Hence, limiting the emissions in terms of mg/min would artificially and unrealistically limit the cooking operations even with the best stoves. Therefore, one option is to continue with the earlier guidelines that had longer time averages of 15 mins for some, 24 hours and more for others. More appropriately, it appears that the standard guidelines in terms of scalable criteria are better - limiting to meaningful lower levels of $CO:CO_2$ ratio emissions of CO, PM in terms of mg/MJ, and $PM2.5$ in terms of μg/m^3. The subject of CO emissions has been discussed at length in earlier work on a variety of applications with gaseous fuel for domestic applications (Advantica, 2002) and it is clear that $CO:CO_2$ ratio offers a generality for expecting clean combustion that can be applied even to biomass combustion systems.

On PM2.5, since fine particulate matter is brought into the kitchen by the winds around, the more meaningful criterion for $PM2.5$ should be in terms of mg/m^3. Also, because of movement of members inside the kitchen, a valid indicator for what will be inhaled is obtained from the local $PM2.5$ concentration. Results on $PM2.5$ are discussed in section 16 to follow.

A further point on the emissions of NO_x in biomass combustion systems is that at the flame temperatures of 1200°C, its generation is insignificant and with respect to SO_x, sulphur present in biomass is so low in most biomass that its generation is also insignificant.

Imposition of new WHO guidelines (in terms of mg/min) coupled with World bank fiscal support system may actually work against any possibility of improving indoor air quality if the magnitude of cooking and the power of the stove(s) needed in an average domestic environment are not factored into the guidelines.

14 Inclined grate gasification-combustion systems

During the development period, occasionally visitors would pose a question: even if they chose to burn firewood, they would not like to bend down to adjust the fuel on the grate or to look at the status of the fire. They enquired of the loading area can be made at a convenient height of 0.7 m or so. It was indicated that the exit must at least be about 1 m to ensure that in the event of loss of electricity for the blower, the hot

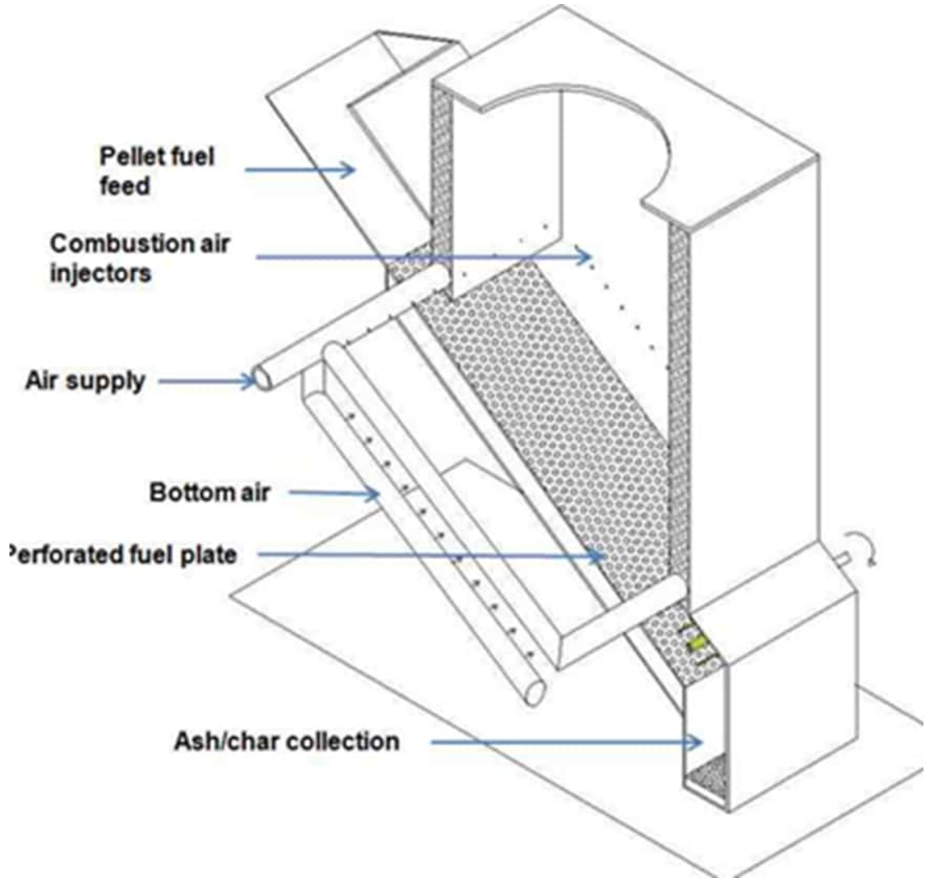

Figure 42: The inclined grate based gasification-combustion system

gases do not find the undesirable pathway along the fuel loading port, something that would not be the case with horizontal fuel loading port as it is currently arranged (see Figures 32 to 34). To meet this expectation, the design shown in Fig. 42 was evolved. This has been built and extensively used in the laboratory for several applications. Subsequently, more uses for this device have been found. One important application is to convert rice or wheat straws or other straws into char so that they can be used to enrich the soil as bio-carbon. The attachment of an automatic feed of a straw mat between rollers would enable steady feed at the rate at which char is getting produced.

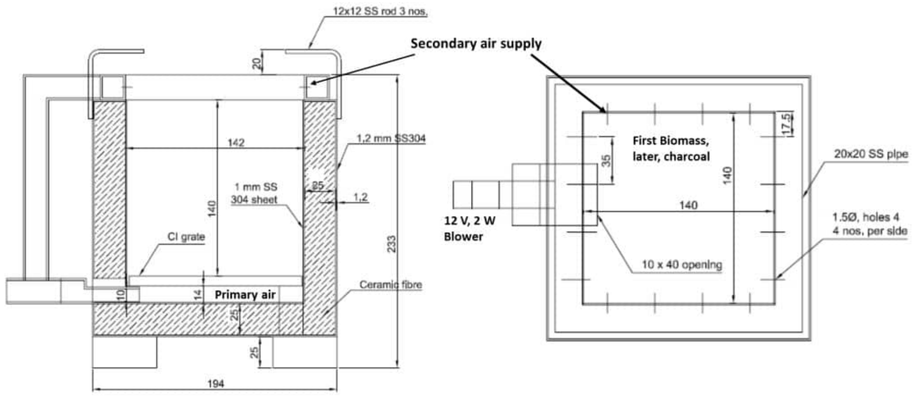

Figure 43: The modified Oorja for burning charcoal with the first load of biomass pieces at 3.5 kWth - 0.9 kg/h biomass and 0.6 kg/h charcoal

15 Clean burning charcoal-biomass stoves

Santos et al (2017) present a conception that charcoal has higher energy density and emission of marginal smoke than firewood. While the former statement is true even though its value for a user is not so important, the fact that it generates marginally higher smoke compared to wood is truly reflective of the poor combustion technology that pervades the region as is true, in fact, of other parts of the World.

Charcoal burning stoves are known to emit large amounts of CO which cannot be seen and hence ignored. Still et al, 2006 document the data of measurements. Also, measurements at the laboratory have shown that free convection based stoves demonstrate that the CO emission jumps up soon after the volatile combustion has got completed. The reasons for this behaviour have been analysed. When volatiles are undergoing combustion, the temperature all across the field is high and there is enough residence time for the combustion of CO, more particularly in the presence of water vapour. In the case of char combustion, the generation of CO occurs first. At lower temperatures that will occur at low burn rates, it is takes time for the conversion of CO to CO_2 particularly because temperature field in the gaseous phase will not be at values required for the conversion to occur with the allowed residence times. This is the reason that CO will be found in much larger fractions for char combustion compared to biomass combustion. If air is introduced in a such a way that combustion of CO is promoted, the fraction of CO will come down in the exhaust stream.

In order to benefit from known knowledge, one can use Oorja stove itself to work on charcoal. The additional benefit that one gets by operating in Oorja system on charcoal instead of biomass is that one can keep loading charcoal periodically maintaining the desired power level. In fact, one approach would be to start the combustion on wood pieces if pellets are expensive. Once the wood pieces have got converted into charcoal, one can keep maintaining the power level by adding more charcoal. The design for a nominal 3.5 kWth implying about 0.9 kg/h sun-dry wood chips or pellets or 0.6 kg/h of charcoal is set out in Fig. 43. All the elements involved in the system are shown therein. The combustion chamber volume is 3 liters and can take 1 to 1.5 kg biomass itself depending on the density of wood pieces or chips. Typical burn time is about an hour. When the operation enters the char mode, char pieces can be loaded into the reactor and the system can be used for longer durations. While the figure shows stainless steel outer casing, it can be replaced by mild steel or aluminium depending on the local price situation and expectations of the market. The inner chamber is made of thin stainless steel sheet to enable replacement if it degrades. While all other components last several years, the most critical component, the inner sheet is estimated to have a life of 700 to 1000 hours that translates to about an year.

16 Indoor air quality

This is a subject significantly related to the use of cook stoves in kitchens. The significant emissions of CO, particulate matter and polyaromatic hydrocarbons which show up as smoke impact the health of individuals in the kitchen and surrounding living areas. It has been researched for over fifty years. Kirk Smith has worked with scientists from all over the World (see for instance, Smith et al, 2000; Balakrishnan et al, 2013) to build data on the emissions and arguing for improved cook stoves with reduced emissions. The choice of free convection, chimney based mud and metal stoves of 2 pan and 3 pan promoted by many countries has been the consequence. The fact that the indoor pollution does not decrease a whole lot is because the there is a significant difference between laboratory effort and real use. In reality, the nature and quality of the biomass fed is vastly different and combustion can get seriously impaired. This fact does not seem to have been adequately realized not only by researchers involved in the studies, but by funding agencies anxious to improve the indoor air quality in underprivileged class of residences. The only real way that the indoor air quality can be improved is *by actually reducing emissions at the source*, simply because the rest of the dynamics is of passive components through the process of convection (or wind) and diffusion. Two aspects are required to be addressed - the quality of biomass and the combustion process. The issue of the quality of biomass has been addressed in detail in section 4 and Fig. 3 specially. If combustion process is managed with forced convection by using an air-to-fuel ratio a little on the lean side of stoichiometry, both efficiency and low emissions would be achieved. This is what has been achieved in the designs of Oorja, HC^{3}D and VEBCOD. The results of indoor air quality are set out in

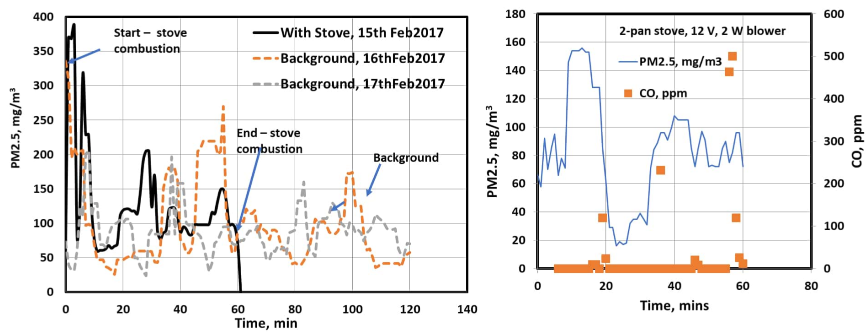

Figure 44: The emission data of HC^{3}D 2 pan combustion system with 12 V, 2 W blower with left part referring to $PM2.5$ in mg/m^3 and right figure on both $PM2.5$ and CO in one of the other tests

Table 6: Emission of particulate matter ($PM2.5$) of HC^{3}D averaged over 1 hour

Condition	Test 1 mg/m^3	Test 2 mg/m^3
Background (2 hours)	113, 120	107, 90
With stove (1 hour)	145	129

Fig. 44. The peak values of $PM2.5$ shown on the left of the figure are large - going up to 380 mg/m^3, but falling off to about 60 mg/m^3 in 10 minutes and varying over the time with a a few minutes peak of 200 mg/m^3. The background air quality set out in dotted lines show that it varies between 30 and 250 mg/m^3.

On the right, the peak in $PM2.5$ is about 150 mg/m^3 and the lowest about 20 mg/m^3. The background values in this case were large. The difference in the peak values depends on the ignition strategy. In the case of the inset on the left, diesel was first sprayed on the biomass fuel bed and ignited. At this stage air was not turned on. For the figure on the right, the amount of diesel used was reduced and this is why the starting is a bit slow. If we used alcohol, these peaks would be much lower. The background values were higher due to combined effects of wind and local movement of the staff in the laboratory. The data shown in Fig. 44 was used to assess the total exposure, the data was integrated over the time and emission data was obtained. These are set out in Table 6.

The incremental emissions due to the stove operations are about 25 $\pm$ 5 mg/m^3. This is about 25 % of the background values of $PM2.5$. This feature is not entirely new and has been noted by Balakrishnan et al (2013). If it is taken that the background $PM2.5$ emission is zero, the total possible inhalation of $PM2.5$ taken over a day for operation of the stove for say, three hours would be 3 mg/day.

Table 7: European systems for biomass combustion, Nussbaumer, 2003; f_m = moisture fraction

Application	Type	Power kW, MW	Fuels	f_m %	ash < %
Manual	Wood stove	2 - 10 kW	Dry wood logs	< 20	2
	Log wood boiler	5 - 50 kW	Log wood +residues	< 30	2
Pellets	Stoves/Boilers	2 - 25 kW	Wood pellets	< 10	2
Automatic	Under-stoker furnace	0.02 - 2 MW	Wood chips/residues	< 50	2
	Moving grate furnace	0.15 - 15 MW	All fuels from biomass	< 60	50
	Cigar burner	3 - 5 MW	Straw bales	$\sim$ 20	5

17 European biomass combustion systems

Due to needs of heating and cooking, several technologies based on log wood, wood chips and pellets have been developed in many countries independently and marketed. A range of the European technologies has been discussed by Nussbaumer (2003). Table 7 is drawn up using that set out by Nussbaumer (2003).

As can be seen, the moisture fraction is much larger than for sun-dry conditions which is about 10 %. In some applications, as-received material is directly used. Clearly, the purpose of these technologies must be to somehow use the material and not quite efficiently, because as moisture increases beyond 10 %, the energy that goes into drying and raising the evaporated water to the flame temperature is an energy deficit. Upstream technology for preparing the biomass by drying is not considered important. This is true of many large scale systems in Europe and the Americas as also in India as was brought out in section 4. Claims of high energy conversion from the calorific value of the input fuel to delivered product - high pressure, high temperature steam being large does not factor into the reduction in the input energy by not drying the feedstock. Thus, if we calculate the efficiency by accounting for the energy for external drying and then use it in the large combustion system, one would be able to provide 20 to 30 % more delivered heat or electrical energy. This is also particularly telling on smaller systems with effective heat losses not being favourable because of larger device volume and surface area per unit energy delivered. Wood pellets outperforming wood chips is significantly due to the absence of moisture beyond sun-dry values.

Haslinger et al (2010) have set out the statistics of various kinds of biomass boilers being sold in the market. It turns out that roughly 30 to 35 % belong to log wood type, 20 to 25 % wood chips, the rest being pellet based. While log wood boilers have been in existence for a long time, wood chip and pellet based boilers are only about a decade old. The cost of small combustion systems based on log wood cost about 75 %

of pellet based boilers and the price range around 3000 to 4000 USD. The high cost may be related to choice of designs where the metal gets exposed to high temperature corrosive gases and the use of automated controls. And the use of sensors and associated electronics to help control the operation will only add to the costs. In fact, Mandl et al (2017) have specifically developed guidelines for the use of automated controls on wood and pellet stoves. The only real control is in the amount of air flow - both bottom air and secondary air. With ill-defined or significantly varying fuel loading as might happen with logs or large size fuel wood pieces, the basic combustion behaviour will get only poorly dealt with even with better controls. Quality fuel like pellets or sun-dry wood chips of course, will improve the combustion behaviour significantly.

The cost of log wood and wood chips is about 60 to 70 USD/tonne and those of pellets 120 to 140 USD/tonne - double the cost of raw wood (Visser et al, 2020). Because log wood is cheaper and in many areas, wood in the form of fallen branches can be freely accessed and processed at home, many home owners prefer log wood boilers and combustion systems as they are cheaper just as the fuel. Since quality is not always embedded in the process, emissions can result as a consequence of significant departures in terms of moisture fraction and size.

The principles used in the construction of a variety of combustion systems (a), typical layouts of a two stage combustion system with bottom air (b) and similar down-draft system with induced flow of air by deploying an hot gas exhaust fan (c) are set out in Fig. 45 drawn from the work of Schlaffer, McCarry, Schmidl and Haslinger of BioEnergy2020+GmBH (2010).

The *top burning* approach involves bottom air directed into the fuel stock and on the top secondary air. The bottom air may or not intersect all the fuel during the course of the burn. The *through burning* approach is the classical "bottom air" for gasification and "top air" for combustion approach used in Oorja (top-lit down-draft, TLUD) class design. But the system operation does not preclude loading at later times and this can result in large burn rate, incomplete combustion and significant undesirable emissions.

The *under burning* approach is more complex with the burnt gases passing around the loaded fuel. It will create an increasing combustion rate profile with time. The *sideways* system involves gasification across the bed in the bottom region. The combustion of the gases in the region next to an outer cover leads to asymmetric flow behaviour and has the issue of heating up of the loaded fuel. With suitable arrangements one can load the fuel as required in the two cases of "under burning and sideways burning" schemes and in others, the recharging changes the combustion dynamics significantly because the bed is already hot. In fact, none of the approaches shown in the inset a is appropriate for reloading. The inset b of Fig. 45 shows the path of air and flue gas in a more modern system whose only issue is with reloading, because at

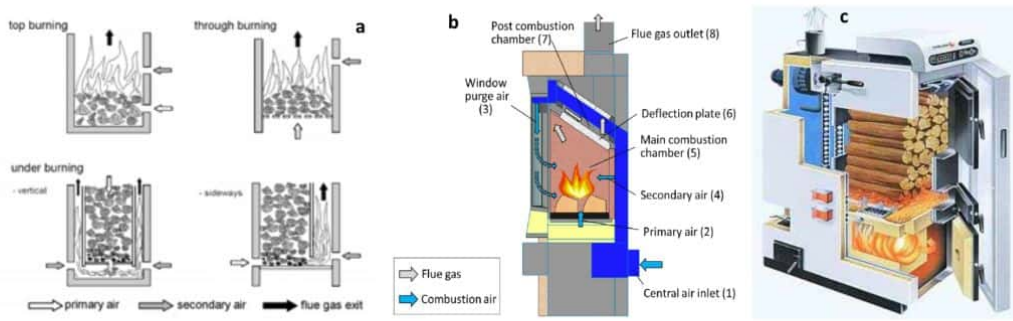

Figure 45: Typical combustion schemes used (a), Air flow and combustion area in a two-stage combustor with boottom air (b) and a downdraft wood log design with air flow induced by the fan located at the exit, BioEnergy2020+GmBH, 2010

that time the entire combustion region will be hot and the burn rates are no longer controlled only by the bottom air because over some time, the entire loaded biomass will receive radiant heat from the walls and burn up at rates not easily determined a-priori. It is only the system like in the inset c that one gets uniform combustion rate every time the fuel is loaded. The only issue with this system is that the moisture content of the fuel can be large as seen from Table 7. Whether it is pellets or wood, the approach used for combustion in design c is the most appropriate in terms of uniformity of burn rate, efficiency and emissions as long as the moisture fraction is limited to sun-dry conditions.

It is important to reflect on the presentation by Nussbaumer (2021) since it discusses developments in 2021 as distinct from the work he presented in 2003. While more fundamentals are covered in this presentation and several problem areas are highlighted, it presents a serious divergence of data between practice and type test data. This position is also reflected in the results of Wohler and Pelz (2017). What they specifically indicate is that while type test method gives 0.2 g/MJ, the procedure simulating the field conditions provides about twice to three times the type test value. This was true for PM as well (0.2 mg/MJ against 1 mg/MJ). Nussbaumer outlines many possibilities by which design and manufacture of the devices can contribute to observed issues. The most serious issues that crop up are related to size of biomass and moisture fraction both of which contribute to the variation in emission performance. The final report of BioEnergy2020+GmBH (2010) was considered very important for adoption in the New York State. The suggestion that emanates from the critical examination here is that such a step is to weighed more carefully.

Jach-Noco et al (2021) have reported some interesting experiments on a special arrangement with moving grate pellet burner mounted in a boiler, where flue gas had a vertical flow via two pass heat exchangers and compared the efficiency and

Table 8: Emissions of CO and particulate matter (PM) from stoves and combustion systems; [a] = Mukunda, 2017; [b] = Jach-Noco, 2021

Nature of system	Fuel	f_m %	Ash %	CO g/MJ	PM mg/MJ
Free convective based designs					
mud, ceramic, metal[a]	Fire wood/agro-residues	< 15	<10	1.5 - 15	$30 - 1000$
Fan based stoves[a]	Pellets	8	<10	0.8 - 1.2	$2 - 20$
Optimized gasifier fan stove[a]	Pellets/Wood chips	8	<10	0.8 - 1.0	$2 - 9$
EU experiments[b]	Wood pellet	8	0.4	0.90	0.20
	Miscanthus straw pellet	9	1.6	0.5	0.18
	Sunflower husk pellet	9	3.4	6.5	2.0
	Corn stover pellet	14	11	1.3	0.4

emissions with wood pellets, miscanthus straw pellets, sunflower husk pellets, and corn stover pellets. While the combustion and thermal efficiencies are high ($\sim$ 93 and about 90 $\pm$ 3 % respectively), the emissions are the crucial factors determining the acceptability in the European countries. The results of the emissions are converted from mg/m^3 at 10 % oxygen into g/MJ as follows.

$$mg/MJ = (mg/m^3 \ at \ 10\%O_2) \times 1.1/[(A/F + 1)H] \tag{1}$$

where H is the calorific value of the fuel in MJ/kg and A/F is the air-to-fuel ratio and the use of $(A/F + 1)$ is to convert the value from the product to fuel. The volumetric unit is converted to mass units by taking the density as 1 kg/m^3. The A/F for stoichiometry depends on the fuel composition (the data for which is unavailable) will be about 6. These results are set out along with the data that was already presented in Table 4 in section 11.6. The results on emissions are correct to the right order of magnitude and adequate for a comparison here. What appears surprising (as also noted by Jach-Noco (2021) is that sunflower pellet alone shows an extraordinarily high CO inconsistent with most other results which are all meaningful. The results of PM for EU experiments are much lower than those done elsewhere because of the method adopted. In EU experiments, the emission was measured much after heat exchangers in the stack. As such, much particulate matter could be expected to retained in the system for the experimental duration. In other experiments, the measurements were made in the open just above the vessel on the combustion system. The reason for doing so is that in domestic open combustion systems food is cooked over the combustion system directly and the emissions will move up with the air current.

In all the studies above, the key aspects of the combustion behaviour of log wood in the configuration in which it is likely to be used (for instance, with air flows as in Fig. 45) should have been explored to determine the flame height which scales as the size of the log wood. This seems to have been replaced with a more complex computational fluid dynamics which can capture gas phase details but only after the appropriate fuel flux values are prescribed. Otherwise, it will show up as either misleading or not relevant.

18 Discussion

18.1 Central issues

With vast improvements in technology over decades, the use of biomass has become limited to rural societies across the World. Urban societies have learned to depend on electricity or piped natural gas or liquified petroleum gas (LPG) for cooking over the last five decades. In the last decade or more, larger segments of rural society in many countries have access to LPG/natural gas for cooking. Even so, the economic level of these communities is such that the families depend on multiple fuels and the back up option as well as larger scale cooking option is always based on biomass in traditional stoves (with significant emissions) essentially because it is lot cheaper this way. Also there is another substantive reason.

Biomass is considered as a fuel that everyone owns and thinks it is for oneself to manage unlike kerosene, gasoline, diesel and liquefied petroleum gas, all of which are supplied by the state. All these fossil fuels have a certain specification to their quality and any deviations can be expected to be corrected. Their known points of availability are widely understood and benefited from. In the case of biomass, firewood stores are around in an urban or peri-urban environment, but the quality of the firewood in terms of moisture fraction that it is available is considered in terms of dry, or mildly wet or wet in the firewood depots. They are provided in "take it or leave it" mode with little incentive for procurement. It is not that they are not expensive, their price varying from 0.06 to 0.12 USD/kg depending on the season and availability. Pellets based either on agro-residues or sawdust are sun-dry and a good fuel, but they are very expensive, about 0.5 to1 USD/kg and are available when orders are placed in reasonable bulk. Energy-wise, they are far more expensive than fossil fuels and thus there is very little motivation to procure and use them. Wood chips are usually not marketed. Thus the key issue in all the world except OECD countries is *main-streaming the solid biomass fuel of quality*. Unless the issue of the accessibility and affordability issues are addressed, modern biomass systems will have difficulty in getting wider acceptance and so biomass based combustion systems can make little contribution to climate change issues.

On the question of whether there are technologies available to use them to deliver efficient and quality heat is what has been addressed in the earlier sections for batch and continuous combustion systems and related aspects are discussed below.

18.2 Biomass combustion systems

The development of clean combustion devices, particularly for the domestic environment has been of interest in most countries over the last fifty years. Progress took place in increments with no significant breakthrough till two changes came about. The first one is related to the ideas. Kaupp's work on gasification tests with rice husk (Kaupp, 1984) that was envisioned as a possible solution by Lafontaine and Reed (1993). This was continued by Thomas Reed and colleagues (Reed and Larsen, 1996) who actually built combustion systems in the late nineties and were propagated as camp stoves. This was because the cost of the stoves was considered unaffordable for the less privileged class of people. Of course, the idea became known.

The next major breakthrough came about because small high speed blower at the level of 2 W became available. This was what that helped realise the clean combustion systems. The batch system led to a product called Oorja by BP, Indi a, the functional aspect of which is the REverse Down-draft Stove (REDS) by IISc in India (Mukunda et al, 2010). The speciality of the design in India was that it was conceived as *a domestic cooking solution*. Such a concept could be realized only with densified fuels. The need for densified fuels was deduced from the following considerations - (a) domestic cooking could extend to about an hour and the fuel needed for completing the cooking at overall efficiencies of 50 % was about 0.75 kg, (b) accommodating the fuel in a small enough combustion space of about a litre for the cooking solution to be effective needed densified fuels and (c) the combustion process should be made independent of the user to ensure that what gets realized in practice is what has been conceived without errors of ignorance being committed. The delivery of the cooking solution needed the production of pellet fuels based on agro-residues to ensure that renewable nature was set into the concept itself. The design of Thomas Reed and colleagues was popularized as Top Lit Up-draft stove (TLUD) by Dr. Anderson in the USA and elsewhere, largely in Africa.

The domestic continuous combustion system through two designs namely HC^{3}D and VEBCOD were developed using partial gasification principles by benefiting from the Sunon 2 and 12 W blowers and these designs have allowed the use of a wide range of fuels. This know-how was scaled up to larger power levels and these systems have received commercial adoption in India. Emissions from the systems in terms of CO and $PM2.5$ have been measured and they are low.

The European resolution for clean heating which was as important as cooking because of climatic conditions compared to tropical countries like India and some parts

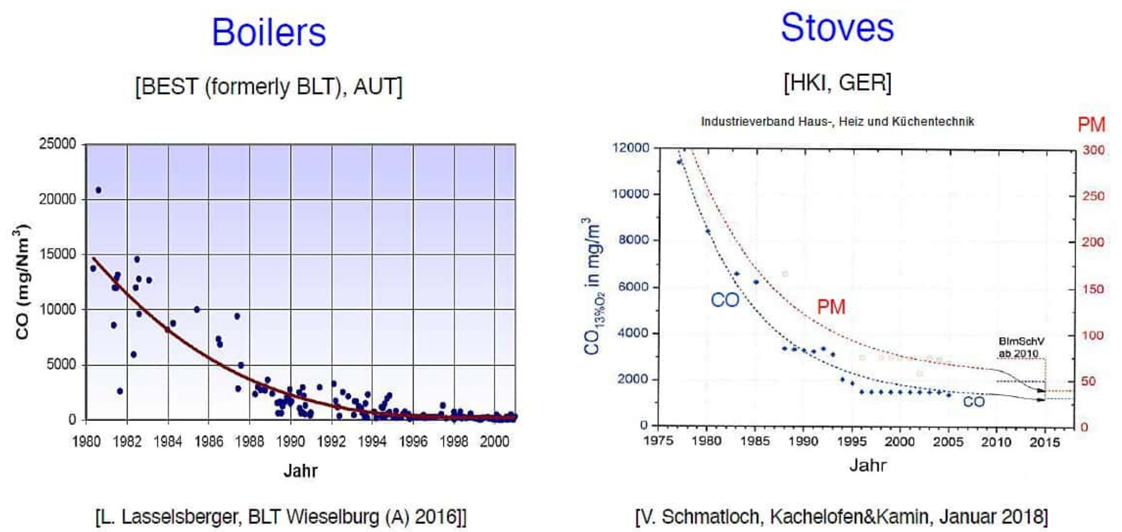

Figure 46: The CO and PM emissions from Boilers and Stoves in Europe over the last five decades, Drawn from Nussbaumer, 2021

of south east Asia, in the early stages, was based on free convective approaches when electricity was unavailable in many parts of Europe. However, the switch to electricity based devices became the norm, slowly. Nussbaumer (2021) quotes other studies on the emissions of CO and PM in boilers and stoves. This is set out in Fig. 46. This figure has interesting results. The emissions were very large in earlier times and technology interventions have reduced the emissions substantially. The reduction in emissions from boilers is very much more than in stoves and in fact it has reached asymptotically small values. In the case of stoves, it has reached in 2015 an average of about 1200 mg/m^3 for CO and this amounts to about 11 - 13 mg/MJ which is still way above what individual systems can achieve ($\sim$ 1 to 3 mg/MJ). Perhaps, this may be because new technology had still to penetrate the field level users. The PM levels are much lower $\sim$ 0.5 mg/MJ which is acceptable as it meets the standard. As explained in Table 8 in section 17, these levels are the same as obtained in fan based small combustion systems described in section 12.3 and subsequent discussion.

A number of manufacturers produce and market the European systems (BioEnergy2020+GmBH, 2010). The key lacuna in the developmental approach in Europe is the lack of understanding of the scientific underpinnings of the combustion systems in practice. Several principles of combustion seem to be deployed and excepting one scheme, others have a complex combustion behaviour in terms of burn rate. The burn behaviour controls the flame temperature and emissions. While type testing performed with a well defined fuel structure, particularly when it concerns log wood, might turn out to show the system as good, the system will perform differently (poorly, as well) when the biomass distribution gets altered due to the choice of the fuel by individual user, a feature known to some research teams in Europe. The computational fluid dynamic simulation being practised in IEA32 initiative is not particularly relevant since it does not integrate the computational study to the fuel geometry which controls the operational behaviour.

18.3 Charcoal stoves

Charcoal stoves prevalent in Africa and South east Asia and north east India need to be replaced by the HC^3D class systems meant for continuous operation in clean mode both in view of sustainability of the local environment and climate change issues. At the very least, it is important to replace the cooking operations by advanced charcoal stoves, of the Oorja kind so that the stoves can be used with little emissions with second and subsequent loadings being of charcoal.

19 Concluding remarks

This chapter is about the progress made on biomass combustion technologies and associated implications in terms of clean combustion adoption to replace fossil fuels in a sustainable manner. World over, nearly a third of the families continue to depend on biomass for cooking even with the availability of cooking gas. The considerations that demand the attention on science and technology of development are: Efficiency, indoor emissions, emissions into the atmosphere, economics of both investment into the device and the the cost of quality fuel.

There is definite progress on the understanding of the combustion process associated with batch and continuous operating systems at various power levels. Several details are summarized in sections 2.6 and 6 and will not be repeated here.

The domestic systems are perhaps the most involved because of smallness of the power level and associated difficulty in achieving low emission, high efficiency while simultaneously making the stove look aesthetically good and affordable. The availability of small size efficient blowers at reasonable cost has made the technical progress possible. Technologically, the development of small size blowers at affordable costs even more than currently available (commercially) would make significant impact on the production of cost-effective domestic combustion systems. With regard to larger semi-industrial and industrial applications, there are several systems that have been built on commercial terms and are working well for years and even as of this writing.

Opportunity exists for producing quality biomass fuels and also deploying a range of combustion devices discussed here both for domestic applications as well as industrial needs. If the Governments consider providing support to the deprived and less privileged group to have start-ups that can acquire the combustion devices in significant numbers, the cost per system can come down and providing support for main-streaming solid bio-fuels for domestic cooking applications will aid in enhancing the use of these fuels in modern combustion systems. This, it can be understood will reduce the magnitude of the use biomass itself due to higher efficiency and replace correspondingly the fossil fuels. These will contribute positively to overcoming climate change problems and also improve the rural health quality.

The fundamentals of moving ahead with providing biomass cooking solutions are simple. Quality biomass supply at affordable prices is a crucial issue. Dried, sized or chipped biomass is a cheaper alternative compared to pellets. Communities can afford to buy these at prices that are regulated, even if not subsidised. Forced convection based continuous combustion systems that perform on emissions better than efficiency are crucial to the new World. Arrangements where a company owns the devices, maintains them through a network and is compensated by the families themselves through a support system for the deprived class, where needed would be useful. It is important that Governments and donor funding agencies concentrate on these aspects to create a self-sustainable cooking solution for the World.

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