Progress report on the research, development and outreach on HC^3D – 2015 to 2017

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Abstract

The horizontal continuous clean combustion device (HC^3D or CCD as it is sometimes termed) for biomass fuels aims to use biomass over a wide range of densities (upwards of 75 kg/m^3) with the only added issue being greater frequency of loading.

During this period when stoves of different power levels – 1 to 150 kg/h have been built by several partners and test run or operationalized in field locations for tens to thousand hours, much learning has taken place and partners involved in the manufacture have definite takeaways from this learning.

1. Very light fuels need a bottom claw device at the grate bottom to enable extract away the ash/char mix that will not leave the space over the grate by itself. Such an operation causes less overall disturbance compared to grate shaking reducing the particulate emissions no matter what the density of the fuel is.
2. Gentle movement of the plate over which the fuel bed rests would be adequate to move the fuel towards the grate.
3. When filling the fuel bed during operation, it is considered advisable to keep the top lip open slightly. This allows the suction from the air ejection system in the combustion chamber draw in the volatiles when that segment of the fuel ignites. As against this, if the top portion was filled completely, the hot top wall would also raise the temperature of the biomass touching it and causes volatiles to be released. These would escape causing unacceptable emissions.
4. Many variants in combustion chamber design are possible. Strong limits on particulate emissions needs that fuel flux across the combustion chamber cross section should be about 100 kg/m^2h (kg/h of biomass throughput divided by the exit cross section) nearly same as in Oorja domestic stove design. However, for applications that connect to boilers or other devices that need greater compactness of combustion without serious limits of particulate emissions from the combustion system can use fuel flux rates up to 350 kg/m^2h. Generally, combustion chambers have square cross section. However, specific applications may need rectangular sections with aspect ratios up to 5. One must be careful in the choice of fuel feed port in such cases as below.
5. The volume of the fuel port should be such as to carry about a third to half in volume (m^3) as the kg/h. To exemplify: a 1kg/h stove should have 400 ± 50 cm^3

of the space and in this space, about 150 to 200 gm of fuel will be present. This condition is nominal for devices that use square combustion chambers. However, if the combustion chambers are rectangular with aspect ratio (width to height) beyond 1.5, it is necessary to restrict the width of the fuel containing region such that the above injunction is obeyed. For a 150 kg/h, 2 m wide x 0.5 m high combustion system (fuel flux maintained at 150 kg/m^2h), the fuel feed port must contain no more than 60 kg fuel. At a packing density of 300 kg/m^3, this translates to 0.2 m^3 of volume. With 0.5 m height and an inclination of fuel port of 45 degrees, the width of the fuel feed port should be 0.8 m (this will be exemplified subsequently).

6. The air supply system must provide for roughly equal rates to the ejector system as well as the bottom. While the bottom air provides for char oxidation and a small part of volatile combustion, the ejector air contributes to the combustion of the gasified combustibles of the char and some volatile that get generated from the top region of the fuel bed. This proportion may get altered depending on the density of the fuel. Dense fuels require more of bottom air compared to light fuels. In any case the ratio is between 60:40 to 40:60.
7. The ejector air velocity is an important parameter. One has a choice of air velocity and injector area to get the same flow rate. Demanding more ejector velocities to create sufficient suction in the combustion chamber area is the aim. Greater demand means more powerful blower – greater electric power demand that will put a load on the power supply system for domestic applications. It is aimed that a chargeable battery system be deployed. This will allow ejector velocities of 10 to 12 m/s adequate for the 2-pan domestic stove system. For larger capacity combustion systems, this restriction is not very critical. For 3.5 kg/h system also one uses a battery operated power supply but can be expected to operate nearly always with electricity being available. For fuel throughputs larger than 3.5 kg/h like 15 to 20 kg/h, 100 kg/h and more, the blowers can be either ring blower of plain centrifugal blowers at power levels of 1 to 5 kWe. One of the questions that comes up for larger systems is the range of jet velocities to be selected. Generally, 30 to 50 m/s should not be difficult. These high velocities provide for a combustion mode called “lifted flame” in which the combustion process is considered far more complete. One of the issues with these high jet speeds is that particle carry over may be more than acceptable There is an intermediate range of jet speeds between 15 to 20 m/s where combustion process is adequate and the particle carryover may be limited. These ideas need to be kept in mind in the design since the interactions are complex.
8. The domestic stove is treated differently from larger power stoves. This is because the domestic stove must meet far more objectives with more stringent criteria. It must be functionally satisfactory, emission-wise meet WHO norms, should look good, last long, should be user friendly, and cost affordable. An industrial system need not meet all these criteria equally effectively. Due to

these reasons, the single pan stove design of 1 kg/h while being available is sacrificed in favor of 1.5 kg/r two pan design to bring the design within the boundary of multi-dimensioned demands.

Results of efficiency and emissions (PM2.5) for the domestic stove and for specific designs of larger pellet combustors will be presented. These it may be noted meet the expected norms of WHO for domestic stoves as will be brought out.

The partners.

There are five partners for stove dissemination at this time. These are:

1. Sustain tech in cooperation with TIDE, Bangalore
2. Harithavani Industries, Bangalore
3. Pheonix technologies, Belgaum
4. Newway industries, Nasik
5. First Energy Private Limited, Pune

Each of these partners has built some systems for domestic and industrial applications over the last year. Both Harithavani industries and Phoenix have been involved in supply of biomass and gasifiers for thermal applications. TIDE with Sustaintech was been involved in its design of free-convection based stoves and project design for societal applications. While First energy private limited has limited itself to pellets without any imposed restriction, others are involved only in a range of non-pellet biomass with either no preparation or limited preparation of drying and sizing. Newway industries was involved in electrical systems design and was working towards design of power sources for biomass based combustion systems. The new philosophy of supply prepared biomass supply along with stoves is the new “mantra” being practiced in the commercialization efforts. This mantra natural to pellet based systems is expanded into as received biomass because most users use “bad” biomass in terms of size and moisture and expect good performance and most stove propagation efforts have ignored the biomass supply as the central need for ensuring good cooking practice. Preparation of biomass to size and moisture content and limiting the ash content by suitable choice of the mix is considered an important element in offering clean cooking solutions to the society.

Biomass used in applications

A variety of biomass was required to be used in applications. These range from tree droppings, cut firewood pieces, agricultural wastes like corncob, coconut husk, sized fronds and cashew shell waste and others. The principal parameters that affect the operation are: density and ash content. The data are set out along the photographs of the fuels tested here.

Tree droppings, about 2 x 3 x 40 mm
Packing density 200 - 210 kg/m^3, ash = 1.3%

Casuarina cut pieces, ~ 11 x 14 x 42 mm
Packing density 240 – 280 kg/m^3, ash = 1%

Corncob ~ 25 mm dia, 30 to 50 mm long
Packing density 200 to 210 kg/m^3, ash = 2%

Cashew nut shell waste, ~ 4 x 20 x 30 mm
Packing density 90 to 100 kg/m^3, ash = 2%

Coconut husk ~ 11 x 21 x 25 mm
Packing density 80 to 90 kg/m^3, ash =2 %

Coconut frond pieces ~ 20 to 40 mm
Packing density ~ 230 kg/m^3, ash ~ 5 %

Continued…

	
Cowdung + sawdust balls 25 to 40 mm dia Packing density 60 to 80 kg/m^3, ash = 8%	**Match stick industry waste 30 mm dia, Packing density 250 kg/m^3, ash ~ 1%**

The problem of very light fuels is that the combustion process occurs by “kilogram” whereas loading the fuel space is by “m^3”. This innocuous feature is based on the thermal balance that heat flux from the flame that causes volatilization or conversion to gas phase is by *heat flux ≈ density of the fuel x linear burn rate x heat of phase change*. If density is low, the linear burn rate is higher and for this reason the changes inside the combustion space occur more rapidly in packed bed situations in lighter fuels. Feeding rate must match with consumption rate so that power is maintained constant, a feature more difficult to achieve in lighter fuels. They need greater attention.

Stoves considered.

The stoves that have been built and tested are (a) 1.5 kg/h two-pan stove, (b) 3 to 6 kg/h combustion system, (c) 12 kg/h combustion system, (d) 20 kg/h combustion system, (e) 100 - 150 kg/h combustion system.

In the case of 1.5 kg/h system, operational performance is available on all the fuel listed in *section 2*. This stove uses a 12 V, 2W battery operated fan of Sunon manufacture (or its equivalent) with a power supply system specially designed for it by M/s Newway industries. The 3 to 6 kg/h combustion system works with Sunon two-stage blower operating on 12 V, 12 W battery designed by M/s Newway industries. This is the way the product is synthesized and operated for cashew shells operating at 2.5 kg/h for wood chips and 4 kg/h for cashew shells. The air supply system has 2.5 mm dia x 30 holes for wood chips and 3 mm x 30 holes for cashew shell operation.

This combustion system is also sometimes coupled to a ring blower for applications like limestone kiln. Under these conditions, it has exhibited 6 kg/h of wood pieces.

The 12 kg/h system that was deployed in a commercial cooking house for use with coconut fronds. The blower used of centrifugal type with a power of 0.75 kW with air delivery pressure head of 100 mm water gauge. The fronds were chipped to varying sizes, very small (less than 10 mm), small (10 to 20 mm) and reasonable (20 to 30 mm). It was suggested that the very small size material should be sieved away as the pressure drop for air flow through the system would be more than can be managed by the blower. Slightly fuel rich operation was overcome through allowing air to be drawn from the lip region of fuel port. It is not clear if the design of the combustion system has been optimized for the operation with fronds, but it is being used in the application as it afforded a far cleaner operation at literally little extra operational expenditure.

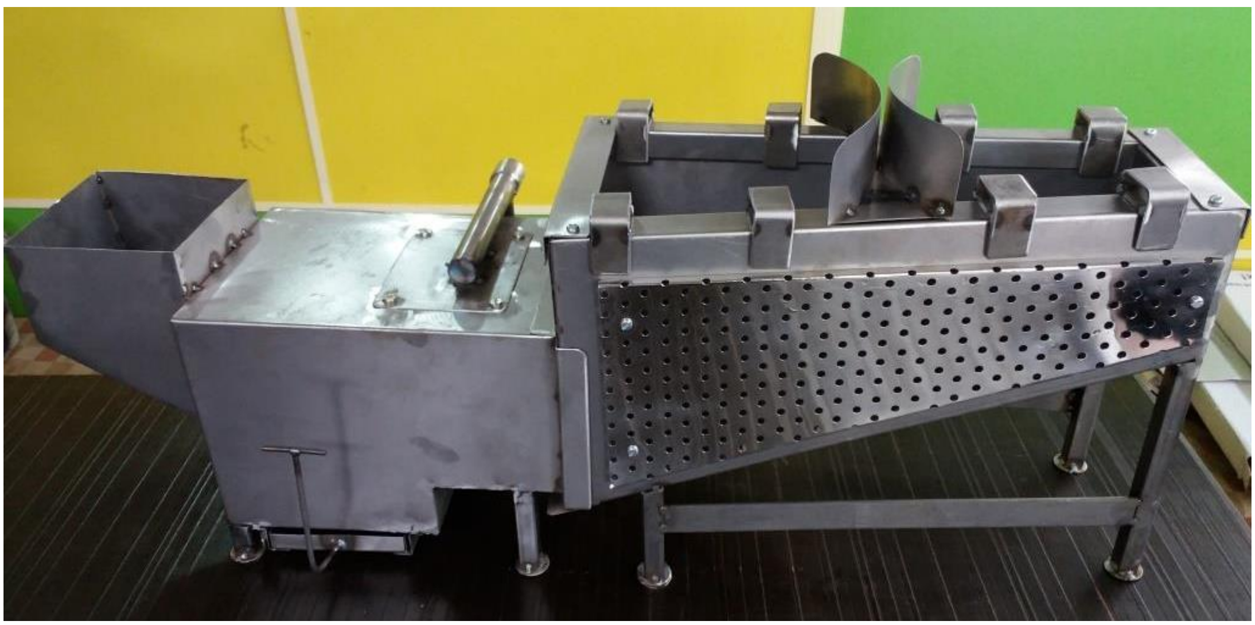

Fig. 1 The 1.5 kg/h system built by Newway industries. The fuel port is at the left end, the combustion chamber next to it with combustion air supply tube seen at the top region and a large combustion space at the right end. The stops seen on the lip of the chamber are supports for the vessels. The curved separators direct the flame on to the vessels. They can be moved to adjust to the size of the vessels. The ash is removed from the bottom using the handle shown below the combustion chamber.

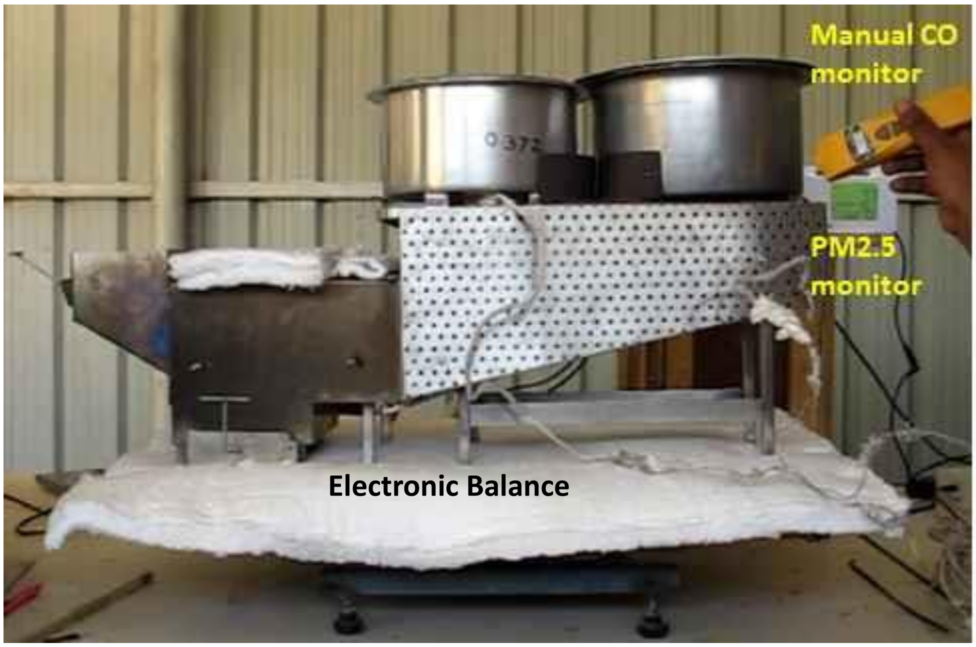

Figure 2. The 1.5 kg/h two-pan balance on test: measurements of water boiling efficiency, emissions of CO and PM2.5 microns. Separate experiments under the hood are co

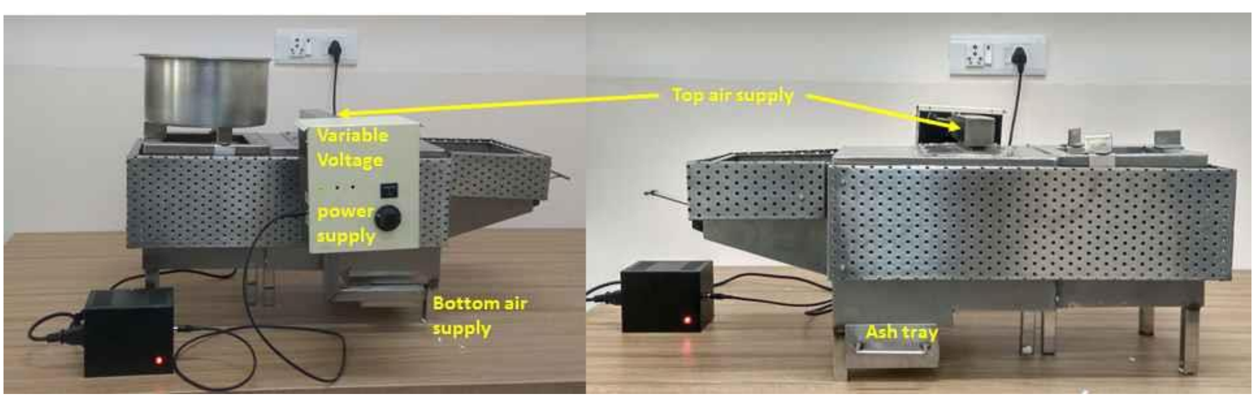

Figure 3. The 3.5 kg/h system with all the details shown. Note the 12 V, 12 W, battery based power supply to run the Sunon two-stage blower inside the power supply box, the locations of bottom and top air supply and the ash tray.

1. **Sustaintech and TIDE**

TIDE and Sustain tech have received a project from Shell India Markets Pvt Ltd to supply them solid biomass fuel for their project. This project is combined with the supply of solid fuel to domestic users of advanced cook stoves (Agnisakhi – 1.4 kg/h two pan system as in Figure 3 manufactured by Newway industries for sustaintech ltd). The operational area is Sidlaghatta, Chikkaballapur district. The fuel under consideration is mulberry stock. Mulberry is grown for providing feed for producing silkworms. Sericulture is a prime activity in this district. The number of stoves planned initially is 200 stoves.

Sustaintech and TIDE came up with a specific request to try out a clean combustion solution for waste cashew shells that were being very wastefully used with serious pollution problems in parts of Tamilnadu (and Kerala as well, but was not a part of the initial effort). The 3.5 kg/h design was tested for cashew shell waste at the laboratories initially at IISc and later in Jain university. The system was run using 40 mm x 40 mm x 56 mm two stage Sunon blower that delivered air at 40 mm water gauge (peak) and flow rates adequate to burn 2.5 kg/h of solid biomass in a clean manner. Cashew shells had some residual oil content that needed higher flow rate of air for combustion. The nominal 2.5 dia holes were increased to 3 mm dia (30 in number). These seemed adequate to burn Cashew shells at 3.5 kg/h. These were explored in locations in Tamilnadu. One such system has worked for over 100 days (about 800 hours). Figure 4 shows the system in operation in the field location.

Figure 4. The 3.5 kg/h system enhanced by TIDE/Sustaintech with an outer frame for placing vessels to meet the local demand for using cashew shell industrial waste as the fuel in commercial kitchen. The vessel on top is for making "idlis" as below:

Figure 5. Idli stand on the stove.

2. Harithavani industries

Mr. Ravikumar has sent the following report on his efforts of marketing the stoves:

"*We tried to implement Agni Mitra in two different locations and different applications.*

a. Agni Mitra 10 Kg/hr for cooking in Peenya Industrial Area - Fuel used coconut shreds.

b. Agni Mitra 30 Kg/hr for condiments in Ragavendra Confectioners, Mysore - Fuel biomass pellets

c. Agni Mitra 20 Kg/hr for condiments in Ragavendra Confectioners, Mysore - Fuel biomass pellets

The 10 kg/h system is operating at a commercial food manufacture location but has problems of smoke from the fuel supply end. This was partly reduced by opening up the space between the hardware and the fuel bed to enable suction to draw the air through this zone. The power appeared lower than with wood chips. With respect to 30 kg/h system, we were not successful at Raghavendra Confectioners due to the following reasons

1. Initially the capacity of the stove was under calculated, hence we could not get the desired results
2. We changed the capacity of the stove to meet the heat requirement
3. Though we could meet their heat requirement there was a short fall of 5 - 10 % in heat requirement
4. Smoke was noticed at loading fuel point"

Figure 6: The 10kg/h system deployed at a food manufacturing place in Peenya. The fuel is coconut husk that was shredded before use. Notice the smoke from the fuel end. The flame was also appeared weak.

This stove was deployed directly at the site without any tests at the factory. The solution that was finally evolved by the user seems to have provided relief. Yet the power performance is perhaps inadequate. Coconut waste have widely differing features. Coconut shell has high density, is a highly lingo-cellulosic compound. And has also some oil components embedded in its structure. Because of this, it needs a larger A/F compared to wood. Coconut husk has a large component of pith that is a powder with ignition and burn up being fast. It has much less ligno-cellulosic components. Coconut frond pieces have features between coconut shell and coconut husk. These aspects need to be researched yet – on the choice of the air-to-fuel ratio, the ratio of bottom air-to-top air ratio and the starting procedure to enable allowance for a reasonable amount of char on the grate so that combustion benefits from the gasification process.

3. Phoenix industries

One investor wanted to build a drier for corncob grit (shredded material) to be used as bedding material for poultry industry and more applications. The aim was to bring down the moisture fraction from 10 to 11 % to 6%. He approached us if a low cost device can be built for his application. It was indicated to him that waste corncobs (low grade variety) could be used to generate combustion gases which when diluted would give gases at temperatures between 110˚C+ by operating a control valve that allows cold air to be mixed with hot combustion gases at around 800 to 900˚C. This was simulated in the laboratory with an existing 3.5 kg/h burning HC3D system. After this, a 10 kg/h system was designed and built by Phoenix industries for Mr. Umesh Devurkar.

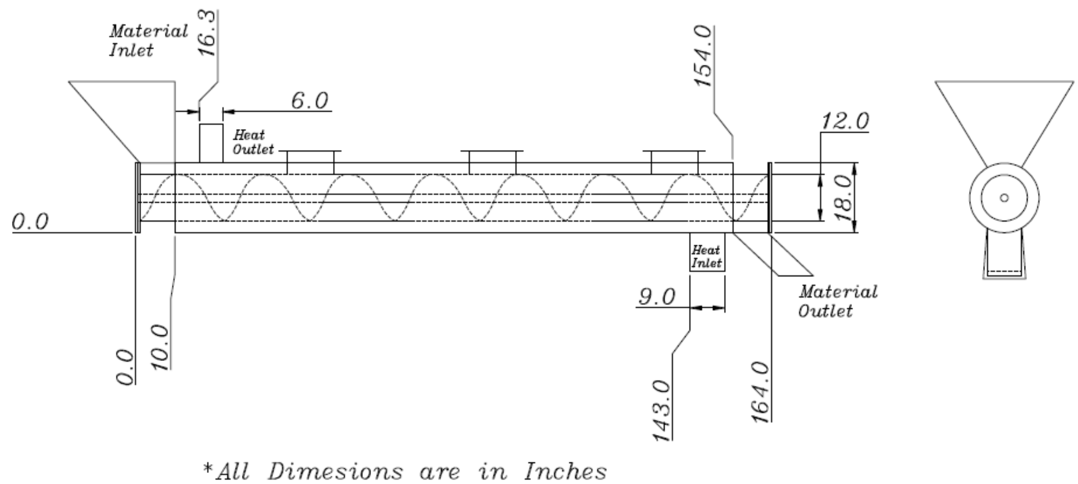

Figure 7: The corncob grit drier design schematics.

Figure 8: The hot air generator using waste corncob based HC^{3}D

The actual system and its performance are set out below.

Figure 9: The field system to corncob grit rotary drier using a hot gas generator using waste corncob as the fuel.

In actual operation, it appears that the combustion system operates at 30 kg/h. It takes about 60 minutes to attain 100 °C in the inner jacket and 60 °C at the outlet of the rotary dryer. The product output is about 200 kg/h. Typical estimates of the efficiency turn out to be about 4 %. The system can take much higher throughputs as productivity demand increases.

4. **First Energy Private Limited (FEPL)**

The staff at FEPL have been in the clean combustion devices for a long time – from 2005 ever since BP India took tech-transfer of what is now known as Oorja domestic stove operating with agricultural fuel pellets manufactured in three places in India, about 0.45 million of which were sold in a subsidized commercial market in several states across India between 2007 to 2010. When BP, India closed its operations, the staff involved in this started a new company called First Energy Private Limited and began their operations targeting commercial establishments for larger cooking heat. This was done in part because the cost of the prepared pellet fuel had risen beyond the affordability of users and could not match the expenditure on LPG. A different model of penetration was adopted to account for varying prices of LPG over a time. The combustion device was leased to them, operated by FEPL personnel with the users paying for the fuel and operational services. This elegant approach has stood them in difficult times when the LPG prices came down. It not often understood that these fluctuations can deeply affect the long term sustainability of alternate energy suppliers like FEPL. While Oorja itself was about 0.8 kg/h, larger systems with 3 to 6 kg/h, 6 to 10 kg/h and 10 to 15 kg/h have been built. These shown extraordinary thermal efficiency.

There main problem is the batch operation. While alternative approaches of using two such systems one-after-the-other have been practiced, it would always be convenient to use a continuous combustion device. In the last three years, two major designs the earlier one called HERS (**H**ybrid **E**iGAS **R**everse downdraft) and the present one AGNIMITRA (or in their terminology CCD) have been adopted by them. All the systems that FEPL builds have varying degrees of automation and control all of which are their intellectual property.

While HERS seems to provide lower particulate emissions, the currently operating CCD offers simplicity of thermodynamic behavior and certain associated fall outs. While the jury is out on what is “better”, more studies are required to establish the points made in favor of CCD. The parameters that are used to compare them are: cost of the system including cost of operation and maintenance, and particulate emissions. At this time, the particulate emissions of CCD in operation are higher than in HERS and these need to be addressed. These are thought to be related to the fuel feed system that has a vibrator that is operated periodically to ensure fuel feed on to the grate. Suggestions to use alternate strategies need to be yet tried out.

They have developed a 12 kg/h deep frying pan system with a chimney to take away the residual gases, a 20 kg/h system that actually runs at 30 35 kg/h coupled to a vapor absorption system of Thermax, and are developing a 100 kg/h system for vapor absorption application of Thermax.

The 12 kg/h system was tested for its operation at the factory of FEPL. Initial tests showed backfire indicating that all the mass flow as not passing through the chimney. After the chimney size was increased suitably, the operation became satisfactory.	 The system in actual operation. Note that the dough is introduced into thin strand producing press that directs the material on to the hot oil. During this operation the machine moves around spreading the delivery of the thin stranded dough. After it is fried it is taken off by a perforated pan into a larger container.

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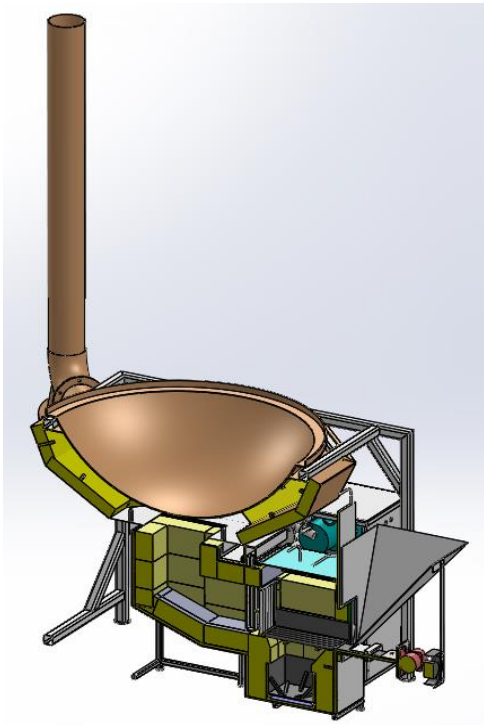
<td>The 12 kg/h system built by FEPL at Pune factory
</td>
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Another view of the system in field</td>
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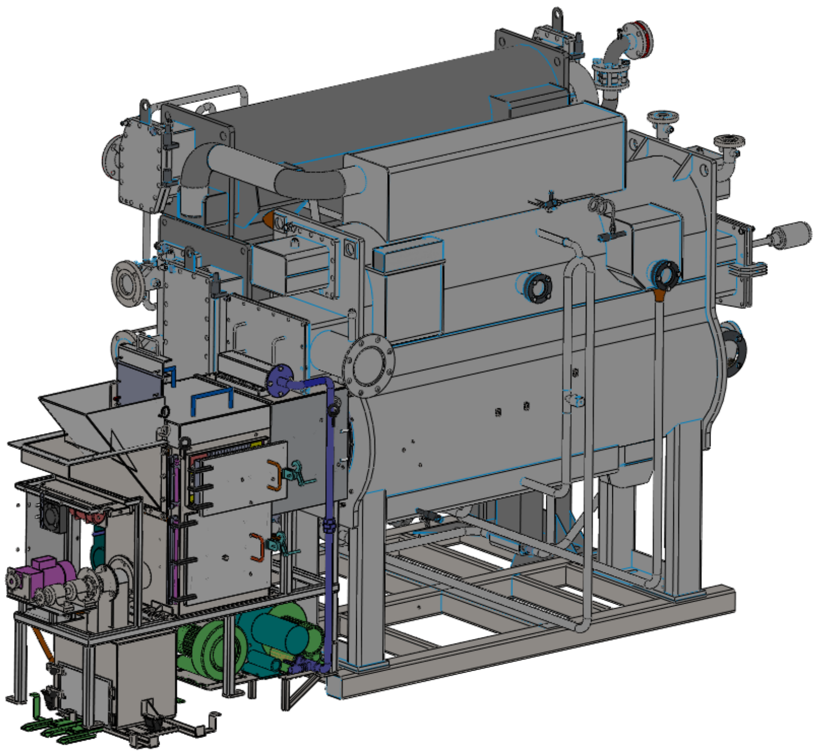
Figure 10. The 12 kg/h system built and tested at the factory before shipment to a field location in Mumbai



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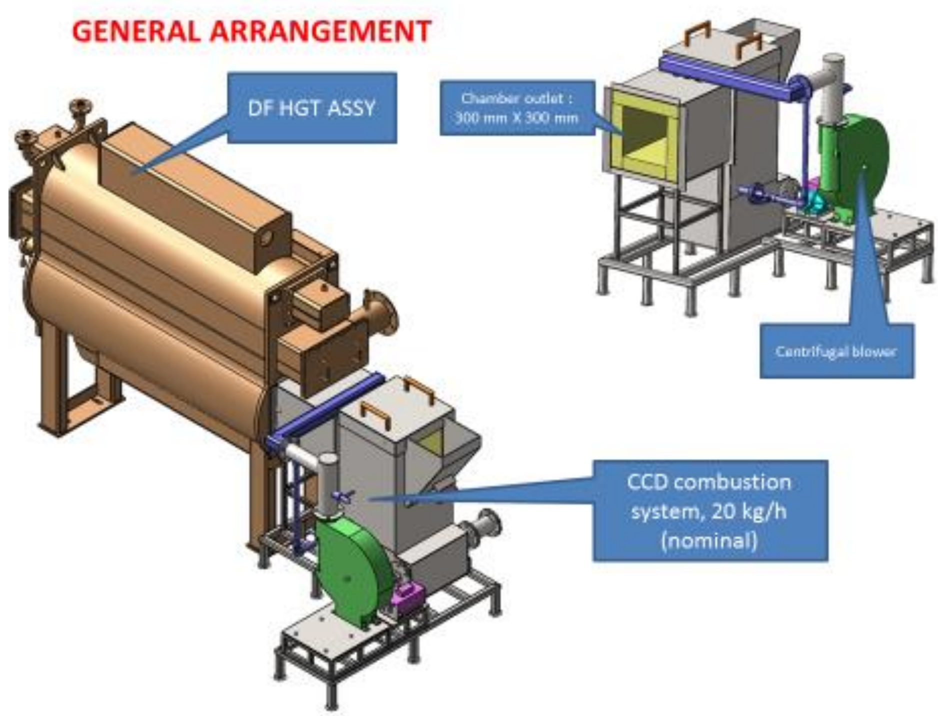

Figure 11 : Assembled system and details of the 20 kg/h (nominal) operating on pellets with Thermal vapor absorption system.

The system integrated with the vapor absorption system has an exhaust fan to draw away the hot gases at around 200°C. In this system, measurements have been made of particulate matter, CO, CO_2 as well as No_x. The results are shown in Table 1. As can be noted the power at which the system has operated is way beyond the nominal design value. The hot gas exit cross section of 300 mm x 300 mm would imply 2220 kg/m^2h as the through put flux. At 33 kg/h, the flux is 366 kg/m^2h. This is perhaps the limit of the use. At these conditions, the combustion intensity is so high going up to 5 MW/m^3 values comparable to other fossil fuel based combustion systems.

Table 1: Combustion and emission performance of the nominal 20 kg/h system

Parameter	Unit	I	II	III	IV
Burner Firing Rate	kg/hr	27	30	30	33
Flame Temperature	°C	860	945	884	893.1
Furnace Temperature	°C	523.0	556	541	594.0
Flue Gas Leaving Temperature	°C	175	186.3	185	184.2
O_2	%	10.2	7.9	7.2	5.4
CO	ppm	12	6	12	16
NO	ppm	250-280			
NO_2	Ppm	<1			
Primary air freq	Hz	25	35	30	35
Secondary air freq	Hz	40	40	40	45
ID fan freq	Hz	50	50	50	50
Vibro motor ON/OFF	sec	3/75	4/80	4/80	3/80
Ash motor ON/OFF	sec	10/50	20/300	20/300	15/300
Slide Gate Opening	mm	60	75	75	100

It can be noted that the oxygen fraction of the exhaust varies between 5 to 10 %. If the excess air is set at around 3 to 5 %, one would get a substantially high flame temperature. An analysis of the data as outlined in Appendix 1 shows that the CO emissions calculate in terms of MJ of fuel energy is about 10 (note that this number may be same as ppm but is in fact different from that value).

Table 1 shows the details of 6 operational systems (mostly HERS) in the field. The total operational hours on these individual systems exceeds 1400 hours as on date (Kolar installation for instance). More systems have been ordered and systems will become operationalized. These systems are nearly Mark 1 class. Small changes have been effected mostly in control system arrangements but the combustion process improvements have yet to take place. Partly, the position that the CCD design is simpler and can be adopted is yet to take roots in the establishment that already has other systems operating reasonably well in the field.

Table 2: Performance of FEPL commercial combustion systems in the field

Customer Name	MG Road	HSR Layout	Kolar	Aathavan	MRF	Anna Uni
Coil/Chimney cleaning date	6/12/'16	21/12/'16	7/12/'16	12/24/'16	3/1/'17	
Coil ash weight in gm	1800	960	2610	340	360	
Chimney ash weight in gm	1990	0	3150	0	2300	
Total Ash wt, g	**3790**	**960**	**5760**	**340**	**2660**	
No of days run boiler	10	6	34	9	7	
Daily Bags consumption	67	36	238	40.5	49	
Mass of pellets, kg	1675	900	5950	1012.5	1225	
PM	0.23%		0.10%		0.22%	
Chimney cleaned?		No		No		
Coil/Chimney cleaning date	29/12/'16	30/12/'16	5/1/2017	4&7/1/'17	12/1/'17	2/1/'17
Coil ash weight, g	2980	1600	1400	150	160	
Chimney ash wt, g	3600	0	2800	4800	1800	
Total Ash wt, g	**6580**	**1600**	**4200**	**4950**	**1960**	**60**
No of days run boiler	19	8	26	22	6	
Daily Bags consumption	130	52	182	99	36	
Pellets in Kg	3250	1300	4550	2475	900	
PM	0.20%	0.12%	0.09%	0.20%	0.22%	
Chimney cleaned?		No				No
Coil/Chimney cleaning date	09/01/'17	19/1/'17		19/1/'17		
Coil ash weight, g	2070	1350		310		
Chimney ash mass, g	3780	0		470		
Total Ash wt in gm	**5850**	**1350**		**780**		
No of days run boiler	11	10		11		
Daily Bags consumption	80	65		49.5		
Mass of pellets, kg	2000	1625		1237.5		
PM	0.29%			0.06%		
Chimney cleaned?		No				

The 100 to 150 kg/h design

The basic design for a square combustion chamber is the same as for smaller power systems. At an allowed flux of 100 to 150 kg/m^{2}h, the cross section of the chamber is 1 m^2. If the application allows for a square cross section, the grate width can be set at 1 m so that the pre-vertical grate volume is 1 m^3. If the application requires rectangular section as it has happened in two applications – lime kiln and a large puffed rice making system. The needed width was 2 m. Hence the cross section was chosen as 2 m x 0.5 m. The grate was still set at

1m. In the initial design, this made the fuel storage volume with the inclined feed zone about one-and-a-half times larger.

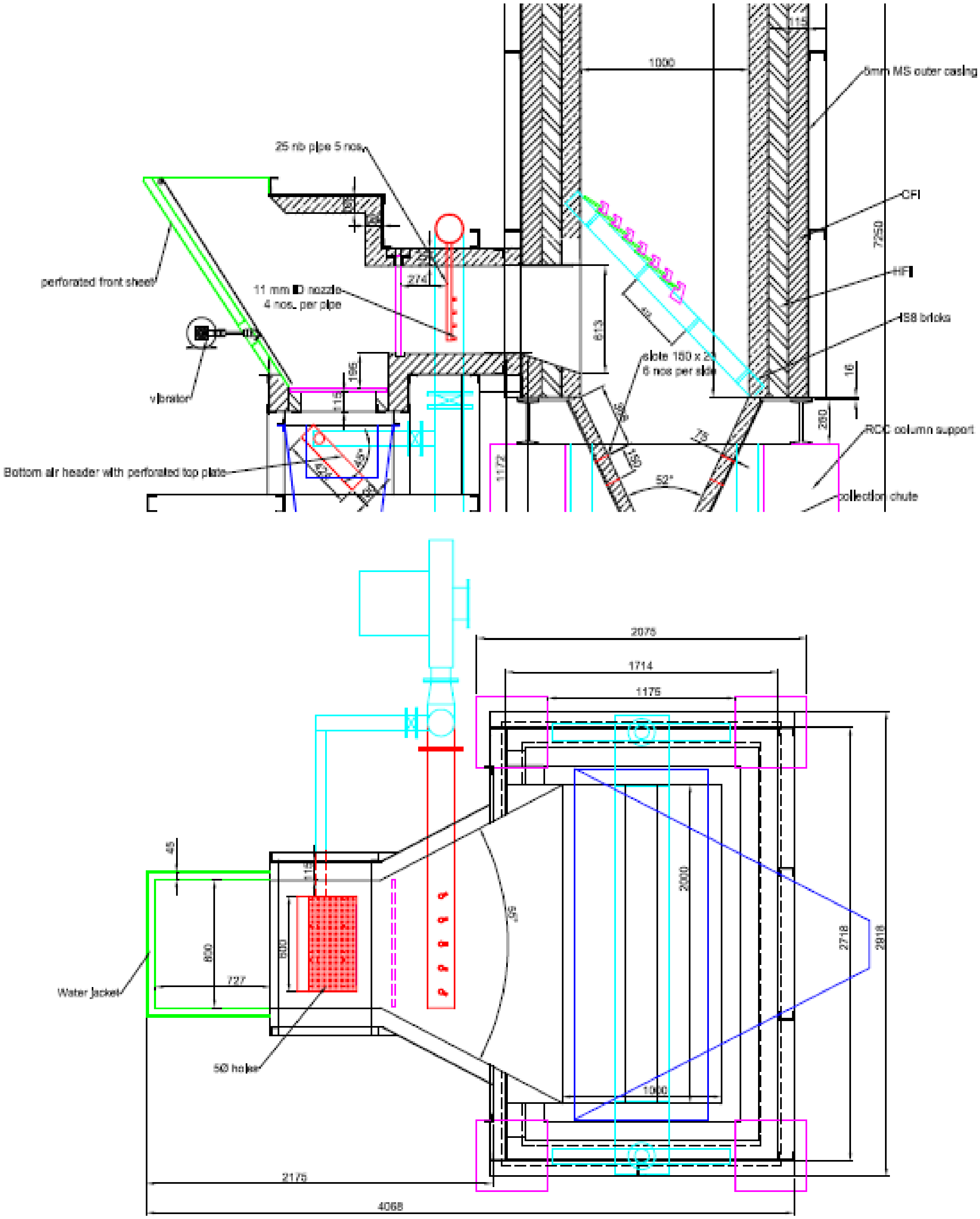

Figure 12: The modified 2 m x 0.5 m cross section based 150 kg/h combustion system with lower fuel capacity in the zone over and ahead of the grate.

This reduces the velocity of the incoming air flow and causes the problem of back flame to be significant. With larger volumes of fuel stored, wind disturbances over the larger cross section can have deleterious effects. The winds can induce lower pressures over part of the fuel bed causing volatile escape via this route and hence larger burn up of the fuel far ahead of the grate. Avoidance of this problem requires that the cross section of the incoming zone be restricted. The modified design of such a system is set out in Figure 12. The fuel feed zone is restricted to 0.8 m wide. Notice that the use of static water jacket around the inclined fuel feed zone helps in ensuring the any uneventful back flame propagation is limited to a small zone close to the grate.

While the original design has been tested for the capacity and performance with the kiln and a simulated combustion zone for puffed rice unit, the modifications have yet to be implemented on the lime kiln unit.

Experiments performed to resolve questions by licensees.

During this period many questions got posed by FEPL, TIDE/Sustain-tech and Harithavani industries. Several of these questions for which studies were conducted and responses were provided are described here.

a. The questions of FEPL related to pellet performance of high density with ash content of 10 % and pellets with very low ash content (~1 %) that caused issues. In the case of higher density pellets, the issue was that the char would accumulate at the grate and not get oxidized and hence reduce the power delivered since fresh fuel could not be delivered to the combustion space. This was inferred to be the case of bottom air being inadequate and using a variable flow control experiments were conducted by Mr. Suri Suresh on a 3.5 kg/h system to determine the behavior with increased bottom air. Surely, the conversion became better and at a certain air flow rate, the char conversion was adequate enough and the combustion system performed for long hours. Further, if the air flow rate was increased even further, there was the problem of ash fusion that would result because the local temperatures would go beyond the ash fusion point. Such a situation as found in experiments at Pune is shown in Figure 13. Thus one would need to operate the combustion system within a narrower range of bottom air flows. A simple measure of this phenomenon is that when bottom air is appropriate, the flame temperatures peak up to 1000°C+. Thus if one increases or lowers the bottom air flow rate such to bring up the temperature to 1000°C and not too much higher, the ash fusion problem would be overcome and the device will operate on a continuous basis.

Figure 13: The 20 kg/h system after about 3 hours of operation. The red hot char has fused and is sitting on the grate preventing further fuel feed and hence reduction in power.

b. A solution was evolved from experiments on 3.5 kg/h HC^{3}D system. These experiments consisted in determining the way the problem can be resolved. Three classes of fuels of different densities and ash content were tested. The results are set out in Table 3. What was observed was that lower density low ash pellets operate smoothly. Higher density pellets show a behavior in which flame temperature comes down with time. This has been linked to the fact that char/ash stays accumulated on the grate not allowing the fresh biomass to come on to the grate. If at this time, char/ash is removed by using a claw, operation gets restored back to the normal level. The periodicity of the operation of claw varies between 10 to 30 s. This can be handled with a control system that checks the flame temperature and when a discernable drop in temperature (~ 100 C) occurs the claw can be operated to remove the char/ash on the grate. There will inevitable particulate emissions through the combustion system, the magnitude of which is comparable to the one with the low density/low ash pellet case.

Table 3: Operational experience on 3.5 kg/h system with different pellets

Type	Opera-tional Hours, hr	Fuel consu-med kg	Char left, kg	Period of ash removal sec	Flame temp, ¤C	Remarks
1	3.2	10.5	0.5	10 to 15	950 to 1110	Stove runs smoothly. Particulate matter observed in the flame
2	4	14	2.5	25 to 30	900 to 1050	Flame temp come down then ash removal is required. The max ash removal up to350 gms. The particulate matter observed in the flame.
3	3	14	2.9	30 to 40	850 to 980	If Flame temp come down then ash removal is required. The max ash removal up to 350 to 380 g. The particulate matter observed in the flame.

1: Low density (450 to 500 kg/m^3) low ash (~1 %) pellets

2: K type – High density ~ 650 kg/m^3 and medium ash (4 to 5 %) pellets

3. High density (600 to 650 kg/m3) and high ash pellets (8 to 10 %) pellets

c. One of the other problems is related to the use of low ash pellets in Oorja class designs, specifically K 150 class systems. The issue was that after a reasonable time of operation when the flame from volatiles were exhausted, the char bed would go dark and the power came down drastically. This was not the case with pellets of higher as content! This issue was not new and had been studies by Dr. S. Varunkumar in his Ph. D thesis at IISc and published as well [S. Varunkumar, N. K. S. Rajan and H. S. Mukunda, Single particle and packed bed combustion in modern gasifier stoves – density effects, Combustion Science and Technology, v. 183:11, pp. 1147 – 1163, 2011]. If the ash content is small, the char particle shrinks lot more and the bottom air oxidizes the material on the grate fast enough for the bed porosity to increase significantly. This increased porosity allows air to flow past the bed without interaction with the bed char and hence, the bed starts becoming colder. The same air that helped oxidation will now act as a coolant and draw away the heat from the material and keep it unreacted. The results are set out in Figure 14. The various cases Exp_01, Exp_02, Exp_03 correspond to the following features.

Exp_1 (22/2/2017) The stove was run on high mode without changing the fan speed. The power supply for the primary fan at 5.11 V.

Exp_2 (23/2/2017) The stove was run on high mode by changing the primary fan speed. Power supply for the primary fan at 5.74 V.

Exp_3 (27/2/2017) The stove was run on high mode by changing the primary fan speed. Power supply is for the primary fan is set at 5.10 V; When the flame temperatures drop down the fan speed was increased to 5.74 V

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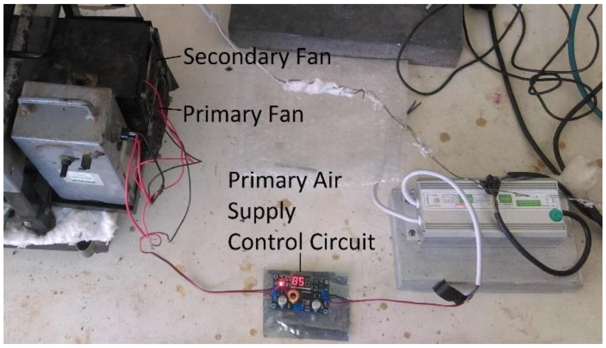
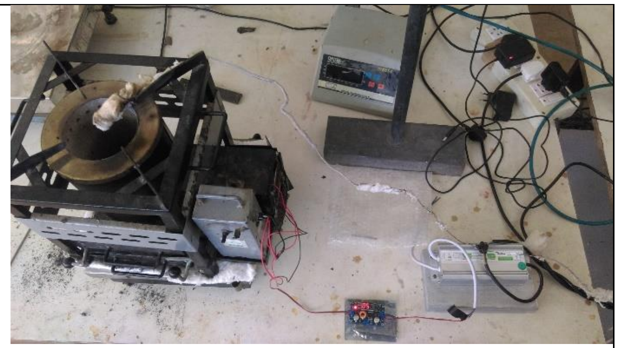


The experiments made on Oorja (0.8 kg/h) system to understand the effects of ash content in pellets. Variable speed control to vary the bottom air flow rate.



The gas temperatures were measured during the operation

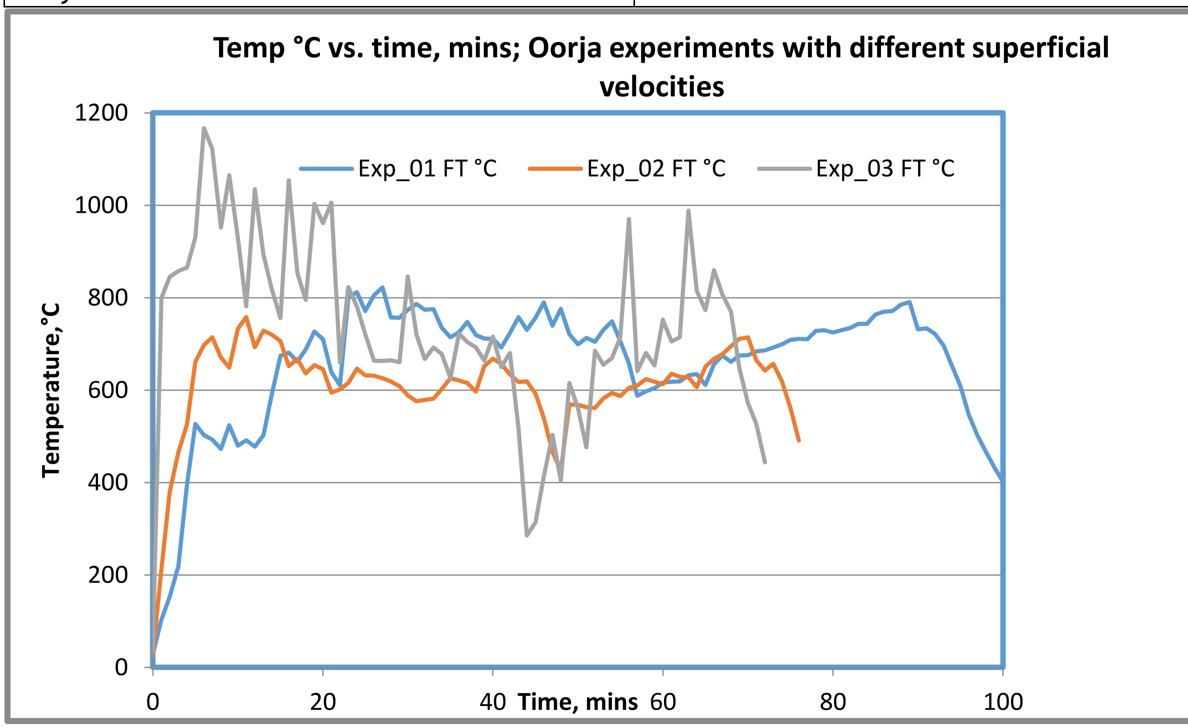


Figure 14: temperature vs time for three experiments with the same conditions till volatile burn out but increased bottom air for Exp 03. Notice it has the shortest burn time largely due to higher burn rate of char.

d. The use of vibrator fixed to the inclined fuel container operated with a periodicity of 2 to 5 minutes to ensure that pellets moved down towards the combustion zone. Whenever the vibrator operated, the particulate emission from the combustion device was very high. As a solution for automatic feed operation it was excellent if periodic emission of hot particles, fine and not-so-fine did not matter to the heat absorption device. If it is a deep frying system, the chimney will carry off fines and the coarser particles will drop-off and collect in various regions in the zone between the combustion system and the frying device. If it is a boiler, the same might be true, but the demand on the periodicity of cleaning the coils, the chimney and other parts of the system would be higher. This periodicity is about 3 weeks at this time. But the demand to make it once-in-four to six weeks is there. This would imply that particulate emissions should be brought down. Two strategies have been suggested – first one is to reduce the ejector jet velocity from 50 m/s class to 20 m/s class. The other one is a split grate. The arrangement is as shown in Figure 15.

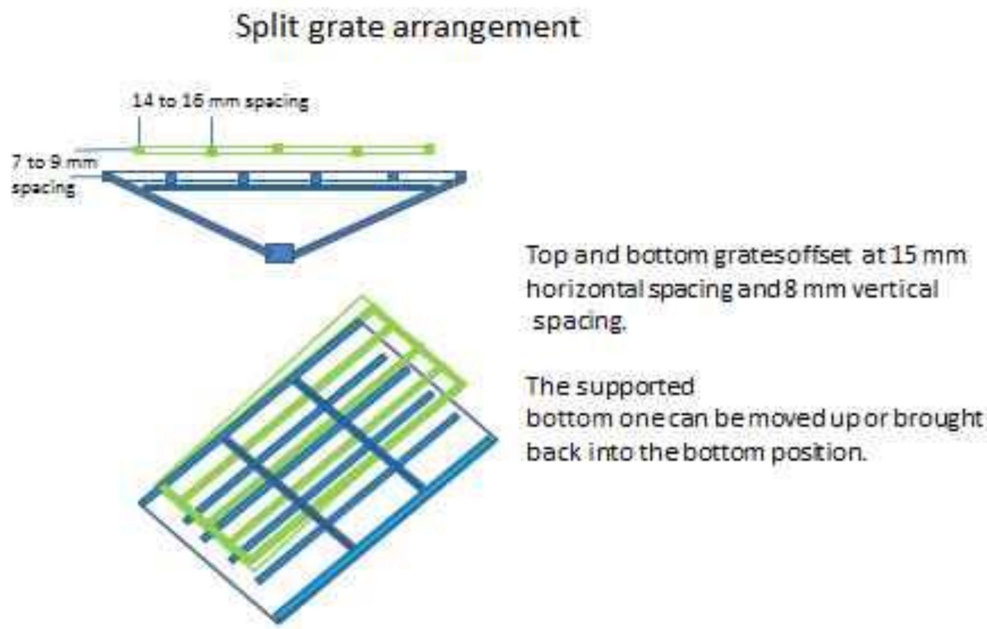


Figure 15 : Split grate arrangement to deal with char/ash removal with little disturbance to the bed.

e. One of the questions posed by TIDE was related to PM2.5 emissions from stoves. WHO has regulations on these emissions and it is expected that “clean combusting stoves” qualify for wider dissemination. The WHO guideline as described in its document indicates 10 μg/m^3 and 25 μg/m^3 for annual mean and 24 hour mean upper limits for particulate matter. [“http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf “]. The mean atmospheric PM2.5 levels all across the country have been explored and seem to exceed this value substantially (S. Dey,L. D. Girolamo, A V. Donkelaar, S. N. Tripathi, T Gupta, M. Mohan, Variability of outdoor fine particulate (PM2.5) concentration in the Indian subcontinent: A remote sensing approach, Remote Sensing of Environment, 127 pp 153 - 161, 2012). In any case, as a device inside the kitchen it is important to deal with this matter and hence a study was conducted at Jain university using the two pan stove.

Suri Suresh conducted these experiments on several days around 20 February 2017. The results form one day are reported here. Because of some not-so-easy-to-explain results on PM2.5, tests were repeated. More tests will be conducted, but are not expected to depart from the present ones.

Duration of run = 60 mins. Amount of wood chips burnt = 1.5 kg; During this period 19 liters was heated to 92 C from an ambient of 26 C and an additional 2.7 liters to 61 C and 4.5 liters to 45 C. The mass burn rate profile is reasonably uniform – constant burning rate. The water boiling efficiency works out to 35.2 %. Emissions of CO = 0.03 g/MJ. $CO:CO_2$ ratio = 0.004.

PM2.5 was measured by the monitor fixed at the height of the cook has a complex behavior. The ambient PM is quite high and varies with wind into the space. It varies from about 45 mg/m^3 without any wind to about 90 mg/m3 with wind into the room. For the PM value to come down from a larger value of 100 mg/m3 to 45 mg/m3 after wind has stopped is about 4 minutes. This perhaps is the response time of the monitor. To make sense of the results, averages were taken for 60 minutes each. While stove experiment was performed on 15th February 2017, blank runs of ambient PM was taken on 16th and 17th February 2017. These data are set out below. The best estimate of PM2.5 emission from stove is less than 30 mg/m^3.

With stove in operation: 7744/60 = 129 mg/m^3
Without stove in operation - day 1 = 12012/120 minutes = 100 mg/m^3
Without stove in operation - day 1 = 10689/120 minutes = 89 mg/m^3
Without stove -day 1 second half = 4726/60 minutes = 79 mg/m^3
Without stove during the first half = 7286/60 minutes= 120 mg/m^3
without stove -day 2- second half = 5332/60 minutes = 89 mg/m^3
PM 2.5 emissions from stove = 25 ± 5 mg/nm^3

These data are the most we can get at this time. There is an important message from this study. The average PM2.5 level without any stove in many kitchens can be as large as 100 mg/nm^3. Therefore, it is important to make measurements of background PM2.5 and then understand the variability more carefully. When this is done, it is expected that Agnisakhi will meet these requirements.

Technology remaining to be exploited.

Figure 16: Hot water generator for domestic applications on a single pan stove. This could also be mounted on 2 pan system or 3.5 kg/h system depending on the demand.

Problems to be resolved in coming times.

There are several questions to be resolved in coming times. These concern PM2.5 related issues and the use of "poor" fuels like coconut residues – coconut husk and fronds. The very low density of the husk and the composition of frond produce some unique combustion behavior that has just been uncovered. These will be explored in coming times. Fuel alteration strategies to deal with coconut pith that can burn up fast and cause issues also need to be addressed. Further, the coconut leaves left behind by users who take away the thin firm strands to make brooms also need to be processed into useful fuel through further processing.

Overview

This report summarizes the work accomplished under the broad umbrella of FEAST. The associates and partners have done many commercial ventures (some adventures as well). Whenever the background studies have been performed, laboratory tests conducted to understand the phenomena involved, puzzles get resolved and solutions of practical nature present themselves. Responding to a good commercial possibility without laboratory of factory testing by directly deploying the hardware is beset with issues to be avoided as much as possible. Making changes in the field is bothersome and expensive. These adventures should be avoided in favor of utilizing the R & D capability of FEAST in cooperation with FCRC, Jain University, Kanakapura campus. Many field related problems have been resolved, but some will come up with wider use. These will be addressed in coming times.

Appendix 1: Calculations of emissions in terms of MJ of fuel energy.

Aim: To calculate the A/F in relationship to stoichiometry and to examine the CO emissions in terms of mg/MJ fuel energy. Other emissions of NOx can also be examined similarly.

To do all these, we must first assume the fuel composition if we have not measured it. We take the elemental composition of fuel pellet as $C\,H_n\,O_m\,N_p$, Typically, n = 1.4 to 1.7, m = 0.6 to 0.7, P = 0.003.

The chemical equation for combustion is

$C\,H_n\,O_m\,N_p$ + $e(O_2 + 79/21\ N_2)$ $\longrightarrow$

$CO_2 + (n/2)\ H_2O + [e + (m/2) - 1 - (n/4)]\ O_2 + [(79/21)\ e + p/2]\ N_2$

The ratio 79/21 = 3.76 refers to volumetric ratio of nitrogen to oxygen.

The mass of fuel is = (12 + n + 16m +14 p). The air-to-fuel ratio for combustion is

A/F = 137 e /(12 +n +16 m + 14 p).

The volumetric oxygen fraction that is measured in the exhaust stream can be calculated as =

(e - 1 + - n/4 + m/2)/(4.76 e + n/4 +m/2 + p/2). This is the same as O_x (like 0.102, 0.079. etc as in the above table). Thus we set

O_x = (e - 1 + - n/4 + m/2)/(4.76 e + n/4 +m/2 + p/2). Solving this for e in terms of Ox, we get

e = [1 + n/4 – m/2 + (n/4 + m/2 + p/2)O_x] / [1 - 4.76 O_x]

If the exhaust stream has O_x = 0, it is the case of complete combustion (theoretically) and

we get

e for stoichiometry = 1 + n/4 – m/2. e – e(stoichiometry) is a measure of the excess air.

The product is given by [1 + (A/F)] kg per kg fuel.

Since CO is measured in ppm (volumetric), we get:

CO (mg/kg product) = CO (ppm) (29/28) = 1.03 CO (ppm)

CO (mg/kg fuel) = CO (mg/kg products) (kg product/kg fuel) = CO (mg/kg products) [1 + (A/F)] =

1.03 CO (ppm) [1 + 137 e /(12 +n +16 m + 14 p)] ; Then

CO mg/MJ fuel energy = 1.03 CO (ppm) [1 + 137 e /(12 +n +16 m + 14 p)] / Fuel cal value (MJ/kg fuel)

Let us take typical values.

n = 1.7, m = 0.7, p = 0.003, Fuel cal value = 14 MJ/kg, O_x = 0.10, CO (ppm) = 10 from above data. We get: e for stoichiometry = 1 + 1.7/4 – 0.7/2 = 1.075.

A/F for stoichiometry = 137 x 1.075 /(12 + 1.7 + 11.2 + 0.072) = 147.3/25 = 5.9

To get O_x = 0.1, we need e = [1 + 1.7/4 – 0.7/2 + (1.7/4 + 0.7/2 + 0.003/2) 0.1]/(1 – 4.76 x0.1) =
[1.075 + (0.425 + 0.35 + 0015) x 0.1]/(0.524) = 2.2
A/F = 5.9 x (2.2/1.075) = 12.1.
We are pushing about 70 – 80 % more air than needed even allowing for some incompleteness in combustion! What will drastically alter the performance is the A/F ratio affecting the flame temperature. It appears that there is much possibility to raise the performance by raising the flame temperature. We should alter the top air-to-bottom air ratio. It appears that reduction in top air by raising the bottom air both slightly will enhance the temperature to 1100 C and hence may contribute to reducing the emissions.

CO (mg/ kg fuel) = 10 [1 + 12.1] = 131. CO (mg/MJ fuel energy) = 131 / 14 = 9.2

Thus CO emissions are about 10 mg/MJ. This is really good performance.

Calculations can be performed similarly for other values of n, m and p. The numbers do not vary much.