

# New Pathways in Clean Combustion of Biomass and Coal via Partial Gasification

H. S. Mukunda and Suresh Attanoor

1 **Abstract** This chapter addresses studies conducted on a new approach to clean  
2 combustion via gasification process progressing on the earlier work on packed bed  
3 reverse downdraft (REDS) combustion. The additional element is the development  
4 of continuous combustion device. The studies are aimed at the use of prepared  
5 (in terms of size and dryness) biomass in a broad range of densities (100 to 1000  
6 kg/m<sup>3</sup>) in a newly conceived scalable combustion scheme. The range of power lev-  
7 els includes domestic demands (~1 kg/h), semi-industrial needs (3 to 20 kg/h), and  
8 larger industrial requirements (50 kg/h and more). System can deliver hot gases at  
9 a flame temperature from 1150 to 1200 °C. In domestic stoves, CO emissions are  
10 within the permissible limits (CO:CO<sub>2</sub> ratio of 0.006 ± 0.002) and PM2.5 emissions  
11 showed incremental steady values of a maximum of 30 µg/m<sup>3</sup>. An important aspect  
12 addressed here concerns the mode of assessment of efficiency and emissions from  
13 these stoves. It is suggested that recent expectations of domestic stove emissions need  
14 revision in favor of known concepts from other combustion devices. The second part  
15 is concerned with the use of coal of permitted ash content (of 21%, but up to 34%)  
16 sized to 2–8 mm for thermal applications and clean cold combustible gas applica-  
17 tions. Studies on the flame propagation behavior in packed beds in REDS with air  
18 show rates about half of that with biomass. With air–steam mixtures, carbon con-  
19 version beyond 99% and avoidance of ash fusion are achieved. Operation of the bed  
20 with heated coal (~120 °C) and air up to 160 °C are considered beneficial to reduce  
21 the flaming time and char conversion times. The fixed bed studies provide inputs for  
22 evolution to mildly fluidizing strategy for complete conversion of coal without ash  
23 fusion.

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455

## 24 1 Introduction

25 Biomass as a source of heat has been used for over several thousand years, even  
26 before coal became a source of energy. Its widespread availability has led to use more  
27 for fire (known as cooking fire classically) and not flame, the distinction between the  
28 two lying in the fact that in the case of fire, air for combustion enters in a free con-  
29 vective manner and in the case of flame, participation of air is controlled by design  
30 through the use of a fan or blower. Combustion of solid fuels has been practiced in  
31 the last hundred years with increased understanding of the processes. Coal as a fuel  
32 was brought in mostly for generating high pressure and high temperature steam that  
33 would run steam turbines to generate electricity. Since it is mined in select places,  
34 it is transported over distances to power stations distributed over various parts of  
35 countries. One of the differences between biomass and coal is that biomass that is  
36 grown widely and wastes are also widely distributed with intrinsic densities between  
37 300 to 700 kg/m<sup>3</sup> where as coal has much higher density of 1100–1400 kg/m<sup>3</sup>. Also  
38 biomass has ash content of a few percent, but coal has ash content varying from a  
39 few percent to as high as 40% (particularly those mined in India). Since transporta-  
40 tion depends on liquid fossil fuels, it has been mandated in India legally to limit the  
41 ash content to less than 34% by coal beneficiation [17] to enable transportation to  
42 what is essential. In the case of biomass, it is particularly important to convert the  
43 potential disadvantage of the higher transportation cost associated with their lower  
44 density into an advantage by seeking arrangements for their use as much locally as  
45 possible.

46 Over a period of time, expectations have arisen on the clean combustion in domes-  
47 tic combustion systems (stoves) and industrial processes. In the case of domestic sys-  
48 tems, limiting the emissions of both PM<sub>2.5</sub> (particulate matter below 2.5 μm) and  
49 CO for combustion systems based on all fuels—gaseous, liquid, and biomass, has  
50 been the demand. For industrial systems, limiting the additional emissions of NO<sub>x</sub>  
51 and SO<sub>x</sub> is introduced for systems based on coal and mixed fuels. Mixing biomass  
52 wastes with coal has been aimed at limiting the emissions as required by the stan-  
53 dards. Seeking higher combustion efficiency of combustion devices and heat transfer  
54 efficiency of heat utilization systems (cooking arrangements of high pressure boiler  
55 or other industrial arrangements) helps limit the emission of CO<sub>2</sub>. The overall  
56 efficiency is measured in terms of kWh/kg fuel (typically 1 to 1.5 kWh/kg biomass  
57 or coal), larger values implying lower fuel consumption for generating the required  
58 energy—electrical or heat and thus lower emission of CO<sub>2</sub>. Reduction in the raw  
59 fuel used to generate the same output implies reduction in all the emissions. How-  
60 ever, these require careful control of combustion processes more difficult to achieve  
61 with solid fuels compared to liquid or gaseous fuels. The difficulty arises because  
62 fuel related shape, size, moisture fraction, and inorganic content (leading to ash) add  
63 additional features to be accounted for. *The most effective approach toward achieving  
64 greater efficiency and limiting emissions comes from gasification.*

65 The use of coal has always been in thermal power stations at several hundreds  
66 of MWe generation implying combustion systems at large throughputs (typically, a

67 hundred MWe generation system burns 60 to 70 tonnes per hour of coal). Reducing  
68 the emissions has been conceived through complex downstream clean-up units that  
69 can turn out to be very expensive. One strategy to reduce the emissions is to use the  
70 gasification approach. Since the conversion process leads to a gas throughput less  
71 than half of the burnt-gas throughput, treatment processes become more economical.

72 Gasification is a controlled process of thermochemical conversion that uses air  
73 (can also use oxy-steam oxidant for synthesis gas generation) with the first step lead-  
74 ing to a raw or clean combustible gas and the next step involving combustion for heat  
75 or electricity generation in internal combustion engines. The process of gasification  
76 can be thought of as sub-stoichiometric combustion. When air enters a packed bed of  
77 sundry biomass pieces, on ignition, the fuel vapors burn with air to produce products  
78 called flaming pyrolysis products that generate a range of intermediate species. Sig-  
79 nificant amounts of  $\text{CO}_2$ ,  $\text{CO}$ ,  $\text{H}_2$ , and several complex hydrogenated compounds of  
80 carbon and hydrogen will get produced. These gases pass through a bed of hot char-  
81 coal in which the complex compounds will breakdown to simpler molecules that  
82 further react with carbon to produce a mixture of gases that when finally cooled and  
83 cleaned lead to a mixture having by volume, nearly equal amounts of  $\text{CO}$  and  $\text{H}_2$   
84 ( $\sim 20\%$ ), and half of that as  $\text{CO}_2$  ( $\sim 10\%$ ) and rest nitrogen. This composition will be  
85 different if oxy-steam gasification is conducted. With fixed bed downdraft gasifica-  
86 tion systems, the arrangement of the packed bed will be such that the bed of biomass  
87 will later get converted to a bed of charcoal so that the pathway of the gas is consis-  
88 tent with the above description of biomass gasification process. Also when coal of  
89 20 to 25% ash is gasified with air-steam mixture of the best proportions in a fixed  
90 bed, one can get a gas similar to air-biomass gasification. This is because coal at this  
91 ash fraction is more energetic than sundry biomass.

92 Depending on the application, it is possible to improve the quality of the com-  
93 bustible gas. When it comes to use in internal combustion engines, minimizing the  
94 fraction of most of particulates of all sizes and some higher hydrocarbons (from tens  
95 of ppm to a ppm or lower) is needed. Much early work on a novel ambient pressure-  
96 based open-top gasification technology for biomass in qualifying the gasification  
97 systems [8] for small- and medium-sized reciprocating engines with delivered power  
98 levels of 1 to 250 kWe [15] and a high pressure modification for small gas turbines  
99 of 30 kWe [16] have been reported. Considerable work on high pressure coal gasifi-  
100 cation systems have been reported extensively and the current status of the varieties  
101 of issues around it are described in the US department of Energy Web site [5].

102 While one would get an impression that large-scale gasification approaches are the  
103 more appropriate choice for current day needs of most countries including India, one  
104 challenging aspect concerns the large-scale introduction of solar photovoltaic power  
105 generation systems. These are being made cheaper for installation with a promise of  
106 much lower tariffs for the electricity generated. Whether this situation is short lived  
107 is less important than that it breaks into conventional investment planning processes  
108 that may not be very difficult to revive subsequently.

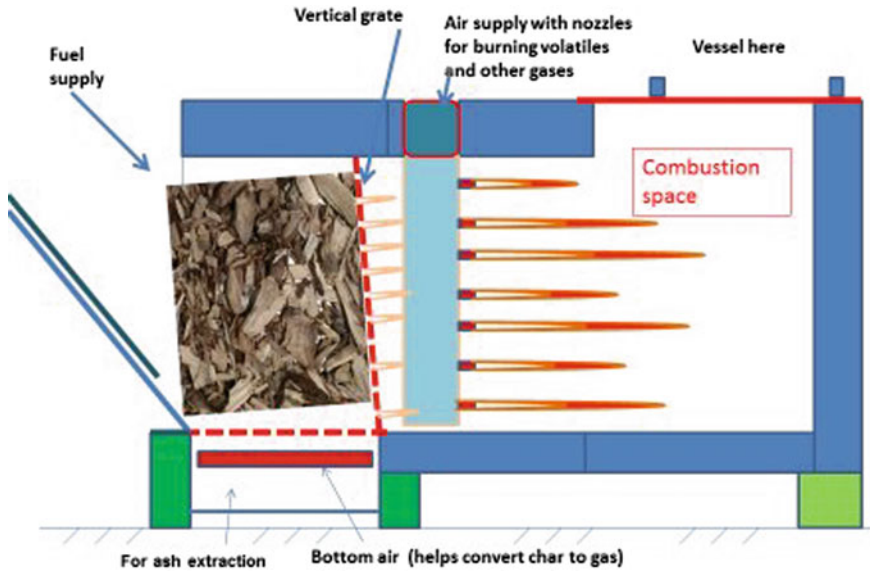
109 It is in this background that one needs to examine alternatives for the need of  
110 biomass and coal in future.

## 111 2 New Avenues for Biomass and Coal

112 It has been known over time that even downdraft biomass gasifiers have been used  
113 more for heat application than for electricity. One of the reasons is that the quality  
114 of gas demanded by turbocharged reciprocated engines is much higher than for nat-  
115 urally aspirated ones, and this is not easy to achieve. A simpler market to cater to  
116 is thermal applications at small to large throughputs and has been achieved signifi-  
117 cantly in many countries including India. Also as distinct from electricity generation  
118 which is pitted against the state in terms of electric supply, delivery of high grade heat  
119 (temperatures of 1000 to 1200 °C) through biomass or coal is pitted against fossil  
120 fuels—liquefied petroleum gas, high speed diesel, or furnace oil (fuel oil) and enjoys  
121 benefits of price of heat including amortization of investment costs being lower. This  
122 area has been green in several parts of India for over twenty years. However, over  
123 time, there have been challenges even here because the global reduction in the price  
124 of the fossil fuels and seeking less expensive solutions *for delivery of heat* from bio-  
125 mass or coal has become attractive in many areas of use. This is where the use of  
126 closely coupled gasification–combustion strategy makes much meaning.

127 Reverse downdraft (REDS) gasification system, otherwise also called top lit  
128 updraft (TLUD) is the first of such ideas when used with pellets of high density offers  
129 a clean and efficient cooking solution if the pellets are made available at affordable  
130 cost. Such a solution is a fire and forget strategy, albeit with moderate power control;  
131 it is a batch combustion process. The operational behavior has been characterized by  
132 [11–13]. A thorough and insightful investigation of the thermochemical processes  
133 and modeling of the operational behavior of biomass-based stoves has been dealt  
134 with by [18]. All these studies are limited to air as the oxidant and sized biomass  
135 pieces of varying density including pellets for the fuel bed. A very important infer-  
136 ence from the studies is that one can achieve the best possible combustion process  
137 for solid fuels of various shapes and sizes. The basis of this inference is that the  
138 gasification process is a self-limiting thermal conversion process. Pieces of biomass  
139 actively involved in the conversion process in the fuel bed can neither generate more  
140 nor less than a mean value because the control is provided by heat flux back to the  
141 fuel. Greater volatilization demands greater flux than available and lower volatiliza-  
142 tion is enhanced because of the availability of larger gas phase heat flux controlled  
143 dominantly by the flow of air through the bed (superficial velocity discussed in [11,  
144 18, 19]).

145 Evolution of these ideas into a continuous clean combustion system was tried  
146 through several approaches, and finally, it led to a horizontal ejector-based system  
147 [10] shown in Fig. 1. Fuel in terms of pieces smaller in size compared to the size of  
148 the fuel port (10–20 mm for a 1.5 kg/h domestic stove and larger sizes for larger sys-  
149 tems) is fed periodically. The initial feed of about a third in height of the combustion  
150 zone is placed on the grate and lit using a small amount of kerosene, alcohol, or a gel  
151 fuel without the fan being switched on. This is because the air currents cause delayed  
152 ignition process. The jets of air maintained at speeds more than 10 m/s cause a low-  
153 pressure zone upstream and so, the gases generated due to the gasification process

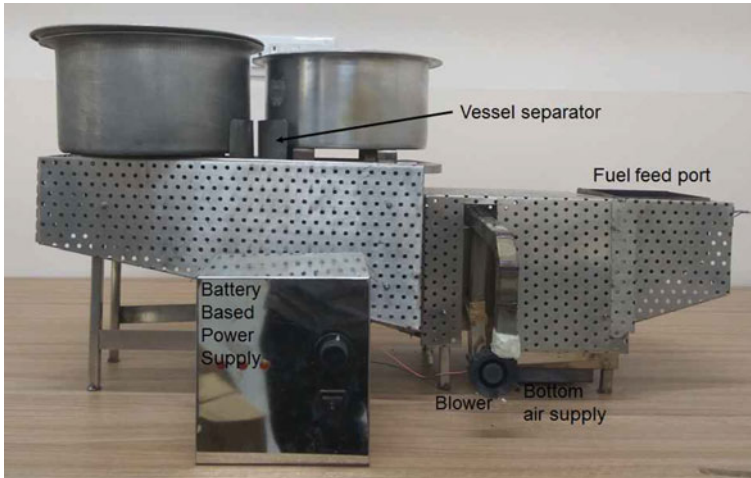


**Fig. 1** Depiction of the principles of the horizontal ejector-based system also termed horizontal clean continuous combustion device

154 are inducted into the combustion chamber where they burn with the air coming out  
 155 of the ejector. Part of the air enters the bottom of the grate to help oxidize the carbon  
 156 of the char left after volatilization. In the steady combustion process, two types  
 157 of processes occur. The first type relates to the char that rests on the grate being  
 158 converted to producer gas before entry into the combustion chamber because of the  
 159 entrainment process. The second part relates to the top of the bed that has some biomass  
 160 also releasing the volatiles. Part of these volatiles enter the combustion chamber  
 161 directly due to air induction and burn up in the combustion zone. In view of the  
 162 combined processes, the total process can be termed quasi-gasification process. The  
 163 air induction process is such that a significant part of the unburnt gases from the fuel  
 164 zone get mixed with the air before final combustion occurs much like in a flameless  
 165 combustion system [7].

166 Full air supply can be turned on a few minutes after ignition. Then, the top of the  
 167 fuel bed releases volatiles, and these burn up in the combustion space downstream  
 168 after mixing with the ejector air that is introduced at speeds of 10 m/s or more through  
 169 3- to 4-mm-diameter holes. After about ten minutes during which period the fuel  
 170 bed generates char over the grate, more fuel can be fed into the fuel space—to fill  
 171 up the entire space. Allowing a small amount of space near the lip of the fuel port  
 172 will permit a small amount of air induction. This artifice enables biomass fuels with  
 173 varying CHNO composition to be burnt in a clean manner. The system will take 10  
 174 to 15 mins from ignition time to attain a steady combustion process.

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**Fig. 2** The two-pan horizontal continuous clean combustion device (HC3D) for domestic use—1.5 kg/h with a 2 W blower operated with a rechargeable battery

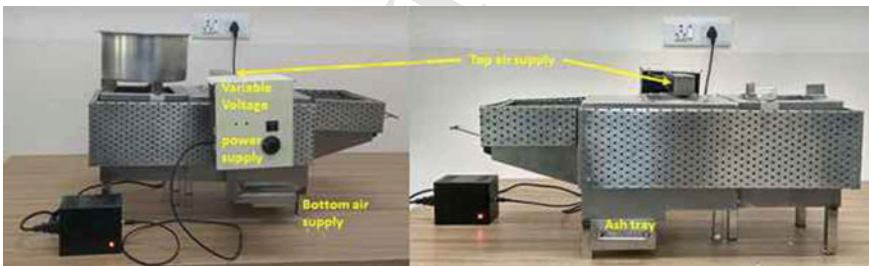
175 The design has been realized at several throughputs—1 kg/h for a single-pan stove  
 176 and 1.5 kg/h is a two-pan stove (that can be seen in Fig. 2, 4 kg/h is a single-pan semi-  
 177 industrial or larger scale cooking system, 12 to 200 kg/h for steam raising and other  
 178 industrial applications. One key parameter that governs the design is the allowable  
 179 mass fuel flux ( $\text{kg/h m}^2$ ) with the reference area being the cross section of the combus-  
 180 tion zone. This fuel flux is typically 100 to 300  $\text{kg/h m}^2$ . Larger values imply  
 181 higher velocities through the entire zone, and this leads to more intense combustion,  
 182 but larger particulate matter carry over. Thus for domestic applications, the flux must  
 183 be set at the lowest and for industrial applications in which the hot gas path has oppor-  
 184 tunity to dump some particulate matter in other zones and allow for a clean exhaust,  
 185 one can choose larger flux values. In one instance, the design for 20 kg/h has also  
 186 handled 35 kg/h of pellet fuel.

187 Figure 3 shows the range of fuels that can be used in the stove. As can be noted  
 188 from the figure, the packing densities of fuels that can be handled are very wide—  
 189 from 100 to 700  $\text{kg/m}^3$ . Fuel costs have the same trend as density with lighter fuels  
 190 being found more easily and the densification process adding to the cost of the fuel.  
 191 Density of the fuel affects directly the periodicity of the fuel feed. The highest density  
 192 fuel needs to be fed at nominal power perhaps once in an hour but the lower density  
 193 fuels every ten minutes or so. Larger systems that are generally for industrial need  
 194 will have automated feed system. The domestic system at 1 to 1.5 kg/h throughput  
 195 is in a sense more difficult to be realized since the expectations are different. Clean  
 196 combustion and continuous operation have to be coupled with reducing the initial  
 197 cost of the device to ensure affordability of the community expected to benefit from  
 198 it. Without automation, the limitation is that those who wish to use this device with





**Fig. 3** Fuels that can be used in HC3D combustion systems: **a** cut tree droppings along with bark, packing density of 200 to 210 kg/m<sup>3</sup>, **b** cashew chopped pieces, packing density of 240 to 280 kg/m<sup>3</sup>, **c** corncobs, packing density of 200 to 210 kg/m<sup>3</sup>, **d** cashew shell waste—90 to 100 kg/m<sup>3</sup>, **e** processed sawdust–cowdung balls, 60 to 80 kg/m<sup>3</sup>, **f** pellets of a mix of seasonal agro-residues, packing density = 600 kg/m<sup>3</sup>, ash content of all biomass ≤ 5%



**Fig. 4** The single-pan HC3D at 2.5 to 4 kg/h with a 12 W two-stage fan operated with a rechargeable battery

199 the low density fuel (that may be very cheap) will need to pay much larger attention  
200 to fuel feed.

201 While operational performance has been checked for all the fuels, select tests on  
202 efficiency and emission performance have been performed on 10% dry cut pieces of  
203 cashew firewood. AQ3

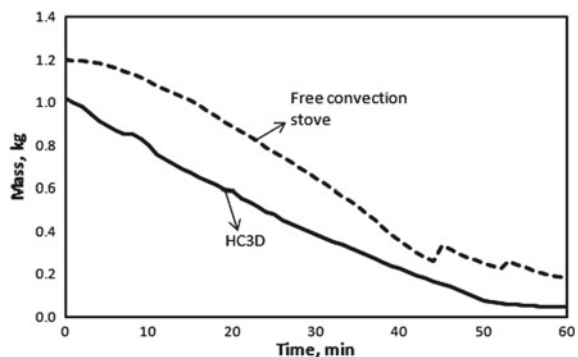
204 Figure 4 shows the views of a 3.5 kg/h system. In this system, fuel sizes up to  
205 30 mm can be used. It has been also used for cashew shell waste in semi-industrial  
206 applications.

### 207 3 Efficiency or Flame Temperature as Performance 208 Indicator

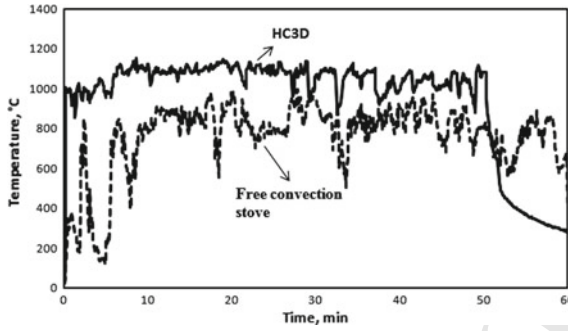
209 Whenever it comes to domestic stoves, water boiling efficiency has been chosen as  
210 the criterion to identify better stoves, classically called improved cookstoves. The  
211 question being brought up here is whether such an approach that has been adopted  
212 world over for over five decades is indeed correct. The issue arises because when  
213 the utilization efficiency is the combined effect of combustion efficiency and heat  
214 transfer efficiency. In order to combine these two for the purposes of standardiza-  
215 tion, flat-bottom vessels of specific sizes are prescribed for tests at specific power  
216 levels. Such an approach seems to be based on a consideration that combustion tech-  
217 nology changes if any, only moderately because most combustion approaches were  
218 free convective based till the last decade. The combustion efficiency of such systems  
219 has been known to be poor, and energy balance studies show that unaccounted losses  
220 are about 30% [14]. These unaccounted losses are essentially due to incomplete combus-  
221 tion caused by large-scale free convective effects (Varun [18]). However, prop-  
222 erly designed forced convection system can increase the efficiency by a factor of 2 or  
223 more and hence one can deliver more power for cooking. Larger cooking pots can be  
224 served with these devices at the same fuel consumption rate. If one were to look at  
225 combustion devices in gas turbine engines for instance, while combustion efficiency  
226 is still retained as one criterion for performance, a more appropriate one that affects  
227 the performance of the system is the temperature distribution at the exit of the combus-  
228 tor. This indicates to the possibility of separating the combustion efficiency from  
229 heat transfer efficiency. If one were to determine the temperature vs time in a zone  
230 where the flat-bottom vessel will be located at one or several locations across the  
231 combustor, one can obtain a very good estimate of the combustion efficiency. Plots  
232 of mass loss versus time and combustor exit temperature from HC3D and a classical  
233 free-convective-based stove are set out in Figs. 5 and 6. The corresponding flame  
234 pictures from the two stoves are shown in Fig. 7.

235 As can be noted, HC3D demonstrates a near uniform temperature of  $1050 \pm 50^\circ\text{C}$   
236 whereas free convective stove shows fluctuating temperatures between  $800 \pm 100^\circ\text{C}$ .

**Fig. 5** Comparison of mass loss versus time between a forced convection stove (HC3D) and a free-convection-based stove in the market







**Fig. 6** Comparison of flame temperatures between a forced convection stove (HC3D) and a free-convection-based stove in the market



**Fig. 7** Comparison between the flames behavior of a free convection stove and the single-pan forced convection single-pan stove (HC3D design)

237 The drop in temperature after 50 min with HC3D stove is due to the consumption  
 238 of 1 kg of the biomass fed. As can be noted in Fig. 5, the mass has dropped to about  
 239 80 gms constituting the final char that takes time to get converted due to relatively  
 240 inferior aero-thermal environment. In the case of free convection stove, this situation  
 241 is caused some time later.

242 The difference in the thermal performance between the two cases is due to the fact  
 243 that fuel generation and air supply are near uniform in HC3D, but widely varying  
 244 temporally in the free convective stove. Smallest of wind currents around the stove  
 245 can cause wide changes in the wall temperature-driven free convective ingestion  
 246 of air into the combustion system. These are directly related to spatial and temporal  
 247 variation of air-to-fuel ratio and the coupled volatilization variation due to fluctuating  
 248 heat feed back. This is also the reason why laboratory tests and field tests show  
 249 substantial differences; one should find much less difference in the case of forced  
 250 convection stoves. These aspects have rarely been understood or acknowledged in  
 251 the large cookstove literature. The more recently born global alliance on cookstoves

discusses a wide variety of issues surrounding clean cookstoves [1] with inadequate scientific inputs from solid fuel combustion science.

Based on these ideas, 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 vessels and of different diameters even in flat-bottom vessels. In fact, the vessel size dependence on the utilization efficiency has been brought out in [13] in which the efficiency improves by 10% if the diameter of the flat-bottomed vessel increases from 220 mm to 300 mm.

Varun [18] has made detailed studies on the heat balance on the REDS stove and shown that out of the input energy, 58% is the useful heat, 21% goes to lost in the flue gas, and 26% is stored in the body of the stove and lost to the environment.

## 4 Efficiency and Emissions

The results of efficiency measurements were made in a water boiling tests were made for 1 kg/h system with aluminum 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 aluminum vessels of 220 and 240 mm dia. Efficiencies of 35 to 38% have been measured for both these systems. Emission measurements of CO, CO<sub>2</sub>, and NO<sub>x</sub> have been made by using a hood arrangement and a flue gas analyzer (FGA 53X Indus system). Also spot mounted instruments were used to make measurements of ambient CO and PM (Optical sensor-based Airveda make with PM2.5 of 0 to 999 μg/m<sup>3</sup> and PM10 of 0–1999 μg/m<sup>3</sup> with relative errors of ±10% and ±10 μg/m<sup>3</sup>).

Complete combustion was assured through the measurements of temperature and oxygen in the direct exhaust stream. These showed values of temperature between 900 and 1100 °C and oxygen fraction between 4 and 6% in various experiments performed to clear the stove for other measurements. The measurements using hood need care in obtaining good estimates of the emissions. 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<sub>2</sub> fraction. The results of experiments on 1.5 kg/h two-pan stove that was run for one hour are as follows. Mass ratio, CO<sub>2</sub>: Biomass was obtained as 1.75 ± 0.05. Measurement of CO gave CO:CO<sub>2</sub> mass ratio as 0.006 ± 0.0015 and total particulate matter (TPM) obtained from the difference in weight of the fine filter material as 22 ± 3 mg (note that this does not include PM2.5 emissions). Separate measurement of PM2.5 in the domestic and laboratory environment showed background values of 20 to 40 μg/m<sup>3</sup> before and much after the experiment. During the experiment, the value went up to 200 μg/m<sup>3</sup> during the light up period of a few minutes and dropped to 25 to 30 μg/m<sup>3</sup> through rest of the duration. A suggestive estimate of the incremental PM2.5 is 30 μg/m<sup>3</sup>. This value is being indicated in this manner because the background PM2.5 in most of the Indian kitchens across the country, more particularly in the northern India is actually very much higher than these values [3], and the presence of a clean burning stove makes

293 little difference to the indoor PM<sub>2.5</sub> levels (levels indicated in Balakrishnan et al. go  
294 up to 1000  $\mu\text{g}/\text{m}^3$ ).

295 The results of emissions can be expressed in other terms as well. CO produced  
296 in burning 1.5 kg in one hour can be expressed as  $1500 \times 1.75 \times 0.006 \text{ g} = 15.75$   
297 g; it works out to 262 mg/min; it can also be expressed as 0.6 g/MJ of fuel energy.  
298 These results are correct to within 25%. Particulate matter (excludes PM<sub>2.5</sub>) is 15  
299 mg/kg fuel or 0.36 mg/min or 1 mg/MJ. Of these results, the scale-independent val-  
300 ues are CO:CO<sub>2</sub> ratio, mg/MJ data and not the values in terms of emission per minute  
301 because this depends on the capacity of the stove (kg/h of burn rate). This is brought  
302 up specially because the recent trends in WHO guidelines [20] indicate to permit-  
303 ted emissions of CO and PM<sub>2.5</sub> in terms of mg/min based on assumptions on air  
304 exchange rates in a standard kitchen. The essential problem with these guidelines  
305 is that the magnitudes limit indirectly the power rating of the stoves even for the  
306 low-emitting stoves. The power level at which the emissions can be met with will  
307 be one 0.65 kg/h stove. Family cooking in India occurs for an average of 5 members  
308 and needs two single-pan stoves of 650 to 750 g/h or two-pan stove of 1.5 kg/h for  
309 about an hour twice daily. This situation may not be universal but sufficiently general.  
310 Hence, limiting the emissions in terms of mg/min would artificially and unrealisti-  
311 cally limit the cooking operations even with the best stoves. Hence, one option is  
312 to continue with the earlier guidelines that had longer time averages of 15 mins for  
313 some, 24 h, and more for others. More appropriately, it appears that the standard  
314 guidelines in terms of scalable criteria are better—limiting to meaningful lower lev-  
315 els of CO:CO<sub>2</sub> ratio emissions of CO, PM in terms of mg/MJ, and PM<sub>2.5</sub> in terms  
316 of  $\mu\text{g}/\text{m}^3$ . The subject of CO emissions has been discussed at length in earlier work  
317 on a variety of applications with gaseous fuel for domestic applications [2], and it is  
318 clear that CO:CO<sub>2</sub> ratio offers a generality for expecting clean combustion that can  
319 be applied even to biomass combustion systems.

320 On PM<sub>2.5</sub>, since fine particulate matter is brought into the kitchen by the winds  
321 around, the more meaningful criterion for PM<sub>2.5</sub> should be in terms of  $\text{mg}/\text{m}^3$ . Also,  
322 because of movement of members inside the kitchen, a valid indicator for what will  
323 be inhaled is obtained from the local PM<sub>2.5</sub> concentration.

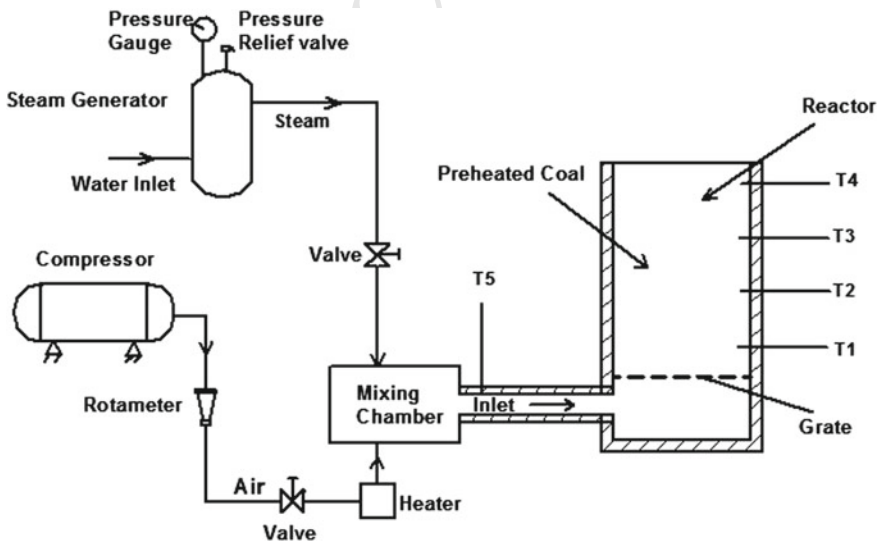
324 A further point on the emissions of NO<sub>x</sub> in biomass combustion systems is that at  
325 the flame temperatures of 1200 °C, its generation is insignificant and with respect to  
326 SO<sub>x</sub>, sulfur present in biomass is so low in most biomass that its generation is also  
327 insignificant.

328 Imposition of new WHO guidelines (in terms of mg/min) coupled with World  
329 Bank fiscal support system may actually work against any possibility of improving  
330 indoor air quality if the magnitude of cooking and the power of the stove(s) needed  
331 to meet the requirement are not factored into the guidelines.

## 5 Insights from Simple Experiments on Coal and High Density Biomass

Coal with varying ash fraction up to 40% has been used in combustors at particle sizes of 70 to 100  $\mu\text{m}$ . Pulverizing coal to this fine size has been known to consume significant amounts of energy. Alternately, coal in larger sizes—typically upwards of 20 mm has been used in fluid bed combustion systems. Such a route has also been contemplated for gasification of coal. Issues of incomplete conversion of char in the coal as well ash fusion problems have been reported ([4]; Khadilkar [6]). Ash fusion is caused by the presence of potassium, sodium, and iron elements in coal but significantly encouraged by larger residence times and larger particle temperatures. On the other hand, shorter residence times lead to incomplete conversion. Based on these considerations, particle sizes of 3 to 8 mm have been considered as an alternate for gasification aimed at achieving near-complete conversion without ash fusion.

Since particle temperatures that matter in the conversion process depend on the flow of oxidizer rich gases around the particles, it was decided to adopt the packed bed approach like the reverse downdraft system (REDS) used for biomass (see Sect. 2) to understand the behavior of a packed bed of coal particles of the above size range. Figure 8 shows the schematic of the experimental setup. The reactor with 73 mm internal diameter and 170 mm length is made of 2-mm-thick mild steel shell insulated outside with alumino-silicate wool blanket. It has four thermocouples inserted laterally at a spacing of  $34 \pm 2$  mm. Steam was generated in an electrically heated boiler to get steam at about 105–110  $^{\circ}\text{C}$  and led through a valve to a mixing



**Fig. 8** Schematic of the apparatus for measuring flame propagation in packed bed of coal and wood pieces

**Table 1** Performance behavior of biomass (wood and coconut shell pieces) and coal in REDS; Wd-o = wood in spheres, Cnut-sh = coconut shell pieces; coal size—see Fig. 10; Sup. vel = Superficial velocity  $m_{ini}$  = initial mass and  $m_{fin}$  = final mass

Property	Wd-o	Cnut-sh			Coal			Units
$\rho_f$	615	850			1250			kg/m <sup>3</sup>
Size,	11	6–8			3, 8			mm
Moisture	10	10			7			%
Ash	1	1			21			%
Volatiles	74	74			29			%
Fixed carbon	15	15			43			%
	Air				Steam–air			
Sup. Vel	19	19	5.7	19	28	43.9	68	cm/s
$T_{air}$	28	155	140	150	155	170	170	°C
Fuel flux	155	470	126	728	960	800	604	kg/h m <sup>2</sup>
$m_{ini}$	144	200	370	285	316	288	292	g
$m_{fin}$	2	2	81	61	75	70	62	g
$\dot{r}$	0.35	0.37	0.17	0.2	0.2	0.18	0.17	mm/s
$\rho_p \dot{r}$	300	311	212	250	250	225	212	kg/h m <sup>2</sup>
$\rho_{char}$	185	342	800	736	729	777	711	kg/m <sup>3</sup>
Steam fr.	–	–	–	–	–	0.29	0.31	–
Steam:air	–	–	–	–	–	0.25	0.27	–

354 chamber. Air heated to 150 to 180 °C in a separate arrangement was also led into  
 355 the mixing chamber through a valve. This arrangement allowed the reactant stream  
 356 to be monitored for its temperature (T5) and led into the bottom of the reactor. The  
 357 mixed hot gas stream would pass through the holes (2–3 mm dia) of a perforated  
 358 stainless steel plate acting as a grate and pass through the bed. The coal used in  
 359 these experiments had an ash content of 21%. The oxidants tested were air at ambi-  
 360 ent temperature and air or air–steam combination at temperatures of 130–150 °C. In  
 361 actual experiments, wood spheres, coconut shell pieces, and sized coal whose prox-  
 362 imate analysis set out in Table 1 are loaded into the reactor. On the top of test bed,  
 363 fine pieces of biomass about 20 g were loaded. This was ignited with a sprinkle of  
 364 kerosene, and after about a minute, bottom air was turned on to a specific superfi-  
 365 cial velocity. The system would acquire steady burning in about six minutes, and the  
 366 conversion process lasted about 25 min.

367 The flame propagated downward in a direction opposite to the flow of the oxi-  
 368 dant. After the flame reached the bottom during which period the coal would loose  
 369 volatiles and the char left behind for the flame to get reversed. This phenomenon is  
 370 the same as what would happen in the case of biomass. The bed height would con-  
 371 tinuously reduce due to volume reduction consequent upon the loss of volatiles and  
 372 finally, with biomass, char would occupy 30% mass and similar height, with coal the



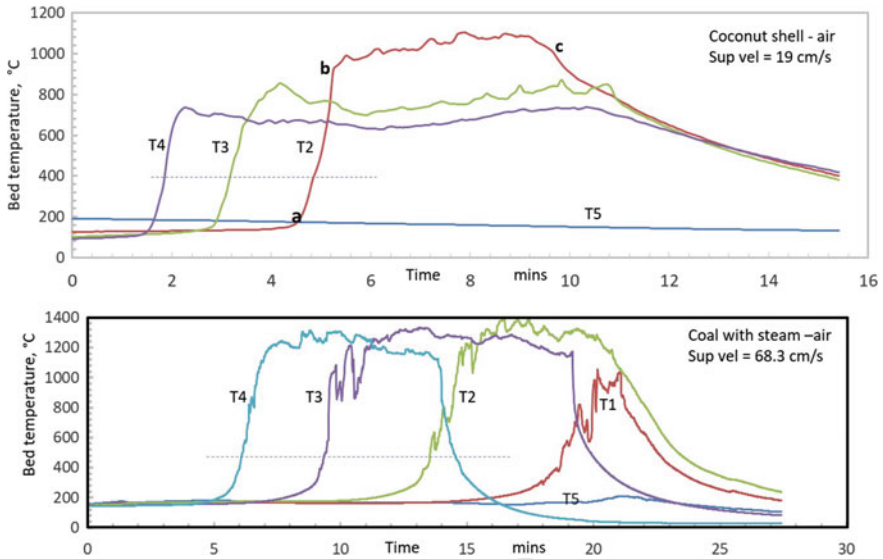


Fig. 9 Temperature versus time at various locations in the packed bed

373 height reduction as well as weight reduction would be about 70%. The conversion of  
 374 char would occur at near-constant temperature depending on the oxidant.

375 Initial experiments were conducted with ambient temperature coal and ambient  
 376 air at superficial velocities between 5 and 6 cm/s. These showed that ash had fused  
 377 into significant small lumps. It was argued that if coal was heated to a temperature  
 378 below the point of significant evolution of volatiles, the conversion process time  
 379 could be reduced. After tests, it was concluded that heating it 120 °C, there was sig-  
 380 nificant evolution of volatiles and so it was decided that heating the coal to 100 °C  
 381 would be satisfactory. Also air or air–steam mixtures would be maintained at higher  
 382 temperatures up to 150 °C. Increase in superficial velocity with air increased the  
 383 possibility of ash fusion. Peak temperatures would go up to 1600 °C, and this would  
 384 inevitably lead to ash fusion problems. Therefore, it was decided to limit the peak  
 385 temperatures by using air–steam mixtures. This would also enable gas composition  
 386 to improve. Several experiments on this were also conducted. The fraction of steam  
 387 in air–steam mixture was varied over a few tests. Broken coconut shell pieces and  
 388 pellets of high density were also used in these experiments to see possible differences  
 389 in the conversion behavior. Figure 9 shows the plots of temperature versus time for  
 390 experiments with coconut shell with air and coal with steam–air mixture. Point “a” is  
 391 the start of the flame arrival at the location of the fuel, point “b” is the completion of  
 392 the ignition process, and point “c” is the completion of the conversion process. Then  
 393 onward there is a decay of temperature due to dominant cooling process caused by  
 394 the flow of air through the system. Flame propagation rate can be estimated by the  
 395 arrival of a specific isotherm at the different locations. The time difference between  
 396 thermocouples at T4, T3, and T2 are 80 and 100 s. For distances between thermo-



**Fig. 10** Coal pieces, hard ash (with some unconverted carbon), and soft ash found in the experiments

397 couples of 33 and 35 mm, we get propagation rates as 0.4 mm/s and 0.35 mm/s. An  
398 average value over the entire distance is 0.366 mm/s. A similar calculation for coal  
399 with steam at the conditions of the experiment shows the propagation rate as 0.17  
400 mm/s. This implies that coal is much less reactive than biomass. Part of this feature  
401 is related to the fact that biomass has 75% volatiles whose conversion is due to gas  
402 phase reactions and coal that has 27% volatiles takes longer to convert because the  
403 solid char to gas conversion is slower.

404 The total conversion time for the mass introduced into the experiment for coal is  
405 17 mins (1120 s) for the coal bed starting from thermocouple T4. This magnitude  
406 is 220 g. Thus, the mass conversion rate is 0.2 g/s. Each particle takes 0.4 s to get  
407 converted considering that each gram has on the average 13 pieces of mean size of  
408 3 mm × 8 mm. This result is useful in the design of the reactor of a fluid bed kind.  
409 Table 1 provides the details and results of the experiments conducted on specific  
410 biomass and coal.

411 The results set out in this table have several features of interest. It is useful to  
412 recognize the well-known differences in density, volatile fraction, and ash content.  
413 The material that was left behind after the experiment on coal is about 21%, the  
414 measured ash fraction of the coal samples used. This implies that the conversion has  
415 been nearly complete. The regression rate at the superficial velocities considered  
416 here has remained nearly constant at around  $0.18 \pm 0.01$  mm/s.

417 A very important inference from the experiments is that with air alone at higher  
418 superficial velocities, ash fusion appeared to be hard. It was inferred that this was  
419 related to peak temperatures going up to 1600 °C. However, with steam–air as the  
420 fluid, the temperatures were limited to 1300 °C with occasional peak touching 1400  
421 °C as can be noted in Fig. 9. In these cases, the ash was soft even if packed and would  
422 break up when handled gently. Figure 10 shows the broken coal pieces used in the  
423 experiments, the hard fused ash in experiments with air at superficial velocity of 28  
424 cm/s, and the broken soft ash from steam–air experiments at superficial velocity of  
425 68 cm/s. At this condition, the bed appeared to be gently buoyant. The converted  
426 ash pieces would fly off from the reactor. Yet, the final condition was such that the  
427 process could not be sustained except as a batch process. It was inferred that it was

necessary to keep the particles separated so that ash fusion could be avoided. In fact, experiments with a reactor with increased height but with superficial velocity of 90 to 100 cm/s, the entire bed remained in an incipient fluidized condition.

## 6 Fluid Bed as an Extension of Packed Bed

A number of preliminary experiments were conducted to determine the operability of high density mildly fluidizing gasification systems for coal. These indicated that at superficial velocities of 1.2 to 1.4 m/s, the packed bed would be expanded by about 25% and as conversion proceeded, the lighter particles would in fact be thrown out. With an attached cyclone the hot gas bereft of particulate matter could be delivered. This system when attached to cooling and fine cleaning systems similar to those developed for biomass gasification systems (see [9]) would help getting engine consistent clean gas. Further work with respect to coal is a part of a separate document.

## 7 Summary

This chapter has addressed the work on a horizontal gasification-based combustion system for biomass for domestic and industrial applications. It is based on exploiting much of clean combustion that comes from reverse downdraft gasification strategy. The horizontal induced draft gasification-based approach is shown to lead to clean combustion over a range of throughputs from 1 to 200 kg/h. This scalability of the approach allows extension to even larger power levels.

The device emissions for domestic applications are indeed low as measured in terms of CO:CO<sub>2</sub> and total particulate matter as well as PM<sub>2.5</sub>. It is suggested that efficiency is best assessed by separating combustion efficiency from heat transfer efficiency. Measuring the combustion system exit temperature profile and relating the delivered heat to the heat of combustion of the fuel will provide the combustion efficiency. The classical water boiling test with vessels similar to the ones used in practice will provide the overall efficiency. Improvements required on combustion and heat transfer can be separately addressed, a feature that has not been practiced in stove developments till now. Reduction in particulate emissions (including PM<sub>2.5</sub>) can be achieved with lower throughput flux as the design parameter (of the order of 100 to 120 kg/h m<sup>2</sup>).

Conduct of flame propagation through packed bed of coal similar to REDS has indicated that the overall rate of conversion is much lower for coal than for biomass—about half the rate of biomass for 21% ash coal. While near-complete conversion has been possible with steam–air mixtures, prevention of ash fusion is possible in bubbling fluid bed operation with superficial velocities of 1.2 to 1.4 m/s enabling separation of particulate matter and extraction through an attached cyclone.

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