Energy Conversion and Management 50 (2009) 955–961

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Solid fuel block as an alternate fuel for cooking and barbecuing: Preliminary results

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ARTICLE INFO

Article history:
Received 23 April 2007
Received in revised form 18 May 2008
Accepted 21 December 2008
Available online 29 January 2009

Keywords:
Cooking
Barbecuing
Agro residue
Fuel block

ABSTRACT

A large part of the rural people of developing countries use traditional biomass stoves to meet their cooking and heating energy demands. These stoves possess very low thermal efficiency; besides, most of them cannot handle agricultural wastes. Thus, there is a need to develop an alternate cooking contrivance which is simple, efficient and can handle a range of biomass including agricultural wastes. In this reported work, a highly densified solid fuel block using a range of low cost agro residues has been developed to meet the cooking and heating needs. A strategy was adopted to determine the best suitable raw materials, which was optimized in terms of cost and performance. Several experiments were conducted using solid fuel block which was manufactured using various raw materials in different proportions; it was found that fuel block composed of 40% biomass, 40% charcoal powder, 15% binder and 5% oxidizer fulfilled the requirement. Based on this finding, fuel blocks of two different configurations viz. cylindrical shape with single and multi-holes (3, 6, 9 and 13) were constructed and its performance was evaluated. For instance, the 13 hole solid fuel block met the requirement of domestic cooking; the mean thermal power was 1.6 kW_{th} with a burn time of 1.5 h. Furthermore, the maximum thermal efficiency recorded for this particular design was 58%. Whereas, the power level of single hole solid fuel block was found to be lower but adequate for barbecue cooking application.

1. Introduction

Biomass is the primary source of energy in the developing countries [1] that supplies 14% of the world's energy, fourth after coal, oil and gas. More than two million people in the developing world use biomass for the majority of their household energy needs, such as for cooking, water heating, domestic space heating, etc. For rural and poor urban people it has remained the main cooking fuel, in spite of the obvious disadvantage in terms of collection effort and household air pollution. The main reasons for this heavy dependency upon biomass fuel are unaffordable price of high quality gaseous and liquid fuel and remote locations of the communities [2–4]. In order to meet the cooking energy demand, they burn the whole range of biomass, such as fuel wood, dung cake, agro residue, charcoal, etc. in traditional cook stoves of varying design. But these traditional stoves are not scientifically designed. They possess very low thermal efficiency [5–7] and also lead to severe health hazards due to indoor air pollution [8]. This low thermal efficiency has a direct impact on total fuel consumption. Hence, in view of the desire for energy saving and requirement for reducing emission and to overcome the shortcomings of traditional stoves, building of modern fuel efficient cook stoves is being attempted the world over. In recent times, a few newer stove designs have emerged, which are claimed to be more efficient than their traditional counterpart [9–11]. Nevertheless, the thermal efficiency is still lower than the fossil fuel based stoves. For instance, LPG and kerosene stoves report a thermal efficiency of 57–61% [12] and 55% [13] respectively. Thus, there is sufficient scope for further improvement of biomass stove in order to match the high grade fuels like LPG, kerosene, etc.

Apart from the issue of thermal efficiency, another drawback of biomass stoves is that most of the designs are fuel specific and therefore cannot handle leafy or agro wastes, which forms a major part of the biomass availability in rural areas. There have been few studies reported with respect to pulverized biomass stoves. Mukunda et al. made a methodical study of pulverized fuel stove [14]. They have conducted parametric studies with respect to optimization of height-to-port diameter ratio, outer-to-inner port diameter ratio and determined the power level dependency on the port diameter as well as the above mentioned ratios. From these data, correlations have been generated for designing a stove for a given power level and a burn time. They also brought up a few issue relating to multiple port design, but not adequately addressed. In the recent times, Dixit et al. carried out a detailed study on both single as well as multi port pulverized fuel stove [2]. Their study demonstrated the feasibility of using multi port stove with leafy wastes as cooking fuel. It was also revealed that multi port

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doi:10.1016/j.enconman.2008.12.031

Nomenclature

m_w	mass of water (kg)	T_i	intital temperature of water (K)
m_v	mass of aluminum vessel (kg)	m_f	mass of fuel consumed (kg)
c_{pv}	specific heat of aluminum vessel (kJ/kg/K)	$L.C.V$	lower calorific value of fuel (kJ/kg)
c_{pw}	specific heat of water (kJ/kg/K)	P	thermal power (kW)
T_f	boiling temperature of water (K)	$\dot{m}_f$	mass loss rate (kg/s)

stove exhibiting better flame stabilization characteristics and posses high efficiency. The efficiency of the stove is reported to be in excess of 37% along with CO and NOx emission to be lower. Moreover, the stove is reported to have operated at near constant power level without use of any external electric device.

Thus, the literature indicates the results of pulverized fuel stove to be promising, yet it provides sufficient opportunity for further work using different types of agro wastes. Hence, based on the work of Dixit et al. [2], it was decided to develop a simplified version which is of high density and compact in terms of design. A simple design of solid fuel block emerged as a natural choice. A strategy was adopted to determine the best suitable raw materials and optimum mixture composition, which meet both the criteria of cost and performance.

Furthermore, this study was extended to address another issue related to the development of an alternate fuel for barbecue (is a process where a large cut of meat is cooked with the help of radiant heating). Normally, this requirement is met by charcoal. In fact, charcoal burning is clean. However, this benefit is greatly offset by higher price and energy inefficient production (30–40% of energy is lost in the preparation of charcoal). This demands an alternate fuel for barbecuing too. Hence, an attempt has been made to develop a charcoal substitute. This paper includes experimental results of the study conducted towards design and development of solid fuel block for cooking and barbecuing as well.

2. Fuel block

2.1. Definition

A fuel block can be defined as a densified mass, primarily made of agro residues, which can be combusted to extract energy for cooking or heating application. A clue for the design of fuel block was taken from the earlier researchers [2,11,14]. The shape of the designed fuel block is cylindrical with either single or multiholes extending from top to bottom. The chosen configuration ensured better flame stability and steady thermal power. The basic criterion to design any cooking contrivance is such that it meets the end use requirement in terms of thermal power and burn duration. The domestic LPG stoves are provided with two burners of 1.5 and 2 kW_{th} maximum capacities [10]. Similarly, kerosene stove with 8–10 and 16 wicks gives out 1 kW_{th} and 2 kW_{th} power, respectively. So considering these figures it was decided to design a fuel block which could deliver about 1.5 kW_{th} power to the pot. Table 1 lists the desirable characteristics of the fuel block for cooking as well as barbecuing. Barbecuing requires supply of low heat over a long duration. It is claimed that barbecued meat/vegetables gives better taste if it is cooked over low heat for a longer duration. Therefore, the fuel block for barbecuing had to be designed in such a way that it operates at very low thermal power over long duration. However, cooking operation need a moderately high and steady thermal power. Hence, in order to fulfill the individual requirements of cooking and barbecuing, a strategy was adopted firstly to select raw materials so that the best suitable raw materials and optimum mixture composition for better performance and economy could be achieved. The following paragraph describes different types of materials that were used for fuel block preparation.

2.2. Materials and methods

One of the constraint imposed in selection of the raw material was such that the fuel block manufactured should be cost effective compared with some of the conventional fuels meant for cooking and at the same time it should possesses a good mechanical strength and show good thermal performance. Hence, the attention was focussed on low cost, easily available biomass such as leafy and agro wastes. In this regard, the individual physical and thermal properties and also the economy associated with different kind of biomass (even though not exhaustive) were studied and finally a few materials had been identified and the effects of each material were studied thoroughly. The list of selective biomass (commonly and easily available) studied is: saw dust, coir pith, powdered leafy dropping like Lucaena Lucochephala and Dendrocalamus Strictus (Bamboo leaves). The other raw materials chosen and their anticipated role in the functioning of fuel block are as follows:

- *Charcoal powder:* to increase the energy and packing density.
- *Binder*: clay, starch, gum arabic: to make the fuel block sturdy and provide integrity.
- *Oxidizer*: potassium nitrate and sodium nitrate: to permit faster ignition.

2.3. Procedure for preparation

The preparation of fuel block involved steps ranging from pulverization of biomass to compacting. The principal steps involved are shredding and pulverizing of biomass for homogenization, mixing of the above identified raw materials with small quantity of water, ramming in a mould to the required shape (with single or multiple hole) and finally drying the fuel block. The size of shredded biomass and charcoal powder was about 1–2 mm and 0.5 mm, respectively. However, binder and oxidizer had to be finely ground before mixing. Fig. 1 shows the block diagram of the preparation of fuel block. The preparation procedure is very simple. First all the raw materials are mixed with little water and then the wet mixture is rammed in the desired mould. After compacting the mould is removed and the fuel block is dried so that its moisture level comes down to ~10%.

Table 1
Desirable characteristics of fuel block.

Property	Barbecuing	Cooking
Ignition time	<2.0 min	
Density	As high as possible, to permit slow burning	
Heat rate (kW_{th})	0.13–0.15	1.5–2.0
Burn time (min)	~40	80–90
Performance	Smokeless operation with high efficiency	

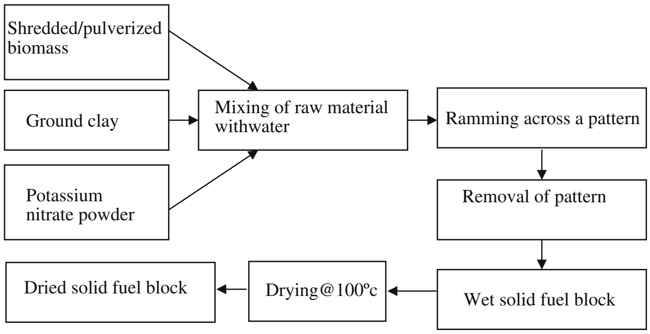

Fig. 1. Block diagram of preparation details of fuel block.

2.4. Working principle

The working principle of the fuel block is similar to pulverized fuel stove. The fuel block operation can be commenced by igniting it at the top by sprinkling a few drops of kerosene. Once it is ignited, the temperature of the block rises and the pyrolysis (loss of volatiles) begins to start. Air flow is established from the bottom due to free convection. The size of the air duct/ducts (hole/holes) was so chosen that the amount of air inside the port is not sufficient to completely combust the fuel vapor released due to the pyrolysis process. Under this condition i.e. the condition of reduced availability of air in the port, the volatiles released through the walls of the hole/holes do not burn immediately with air, but only get mixed and moves up till the outlet is reached, where it burns cleanly. In this case, the flaming process is strictly restricted to the top region only. This mode is referred as gasification mode. Since in this mode the combustion is premixed in nature the quality of combustion would be better. This high combustion efficiency eliminates smoky operation. Unlike this, if the availability of air within the holes of the fuel block is sufficient flame resides inside the holes of the fuel block. This mode of combustion is referred as combustion mode. The gasification mode of operation is more efficient and clean (since it is premixed in nature) and preferred over combustion mode. One can make the fuel block to operate in gasification mode through proper selection of aspect ratio (height-to-hole diameter).

Fig. 2a. Flaming combustion.

Fig. 2b. Flaming combustion.

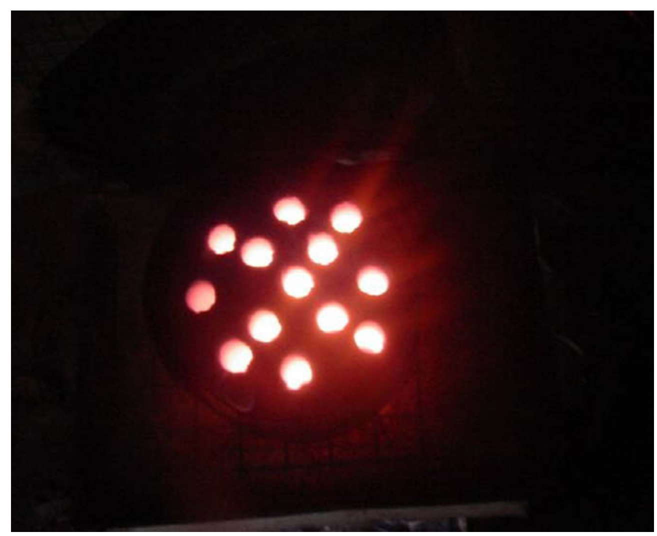

Fig. 2c. Glowing combustion.

Gasification is a two step process. In the first step volatiles are released and burnt at the top leaving behind the charcoal. This process is called flaming combustion. In the second step, the products of combustion, CO_2 and H_2O pass through the hot char bed and get converted to CO, H_2 and CH_4. This process is called glowing combustion. In this step, charcoal glows but no flame is seen. Figs. 2a and 2b represent flaming and Fig. 2c represents glowing combustion. In the following paragraph we describe the experimentation details.

3. Experimental investigations

The experimentation of the current study covers the evaluation of thermo physico properties of the selected biomass, optimization of composition and geometry of the fuel block and the thermal performance evaluation of single and multi-hole fuel block.

3.1. Thermo physico properties of fuel

The thermo physico properties considered here are moisture percentage, ash percentage, bulk density and calorific value of biomass. The moisture and ash content of the selected biomass were evaluated using ASTM method [14,15]. The bulk density of each fuel was estimated by putting a known mass of fuel in a known volume of beaker. The lower calorific value was calculated using the following formula given by Mukunda et al. [10]:

$$L.C.V = (18 - (20 * \text{moisture fraction in biomass}))(1 - \text{ash fraction in biomass})$$

Table 2 includes the thermo physico properties of the four selected biomass. The result shows that the moisture percentage is nearly same for all the bio fuels. However, there is a significant difference in ash percentage which ultimately affects the fuel's calorific value. It may be noted that leafy fuels posses higher ash percentage than some of the agro wastes.

3.2. Thermal performance of fuel block

The thermal performance of the fuel block includes determination of thermal efficiency and average thermal power. The thermal efficiency can be defined as the ratio of energy transferred to the vessel/pot to the energy released from the fuel is determined by standard water boiling test (WBT) where a known quantity of water is heated using thermal power from any stove. In the current study this was done in accordance to the method given by Mukunda et al. [10]. Water was heated through a 65° C (from 25° c to 90° c) temperature rise and the corresponding fuel consumptions were measured for three different load of water viz. 2.5, 6 and 10 kg. Fig. 3 shows the schematic diagram of the experimental setup used for the water boiling test. It consists of a multi-hole fuel block, a weighing balance, an aluminum pan with lid, a stirrer and a thermometer. The following mathematical formula was adopted to determine the thermal efficiency:

$$\eta = \frac{(m_w c_{pw} + m_v c_{pv})(T_f - T_i)}{m_f C.V} \times 100$$

where m_w is the mass of water taken in the vessel, kg; m_v the mass of aluminum vessel, kg; c_{pv} specific heat of aluminum vessel, kJ/kg/K; c_{pw} the specific heat of water, kJ/kg/K; T_f the boiling temperature of water, K; T_i the intital temperature of water, K; m_f the mass of fuel consumed, kg and $C.V$ is the lower calorific value of fuel used, kJ/kg.

In this work, the mass measurement was carried out by a strain gauge based weighing balance (15 kg range and 0.5 g least count) with digital display and water temperature by an ordinary mercury thermometer (range −10° C to 110 ° C, accuracy 1° C).

The same weighing balance was used for determination of mass of the fuel block before and after burning. The difference in weight shows the total consumption of fuel, which gives the indication of average thermal power. The following formula was used thermal power calculation:

Table 2
Thermo physico properties of different biomass.

Biomass	Moisture content (%) (wet basis)	Ash content (%)	Bulk density (kg/m^3)	Av. Calorific value (MJ/kg)
Sawdust	10.1	1.1	250–300	15.8
Coir pith	11.3	2.2	80–100	15.4
Lucaena leaves	11.2	10.4	200–250	14.1
Bamboo leaves	8.4	15.2	300–350	13.8

$$P = \dot{m}_f * L.C.V$$

where P is the thermal power, kW; $\dot{m}_f$ is the mass loss rate of fuel, kg/s and $L.C.V$ is the lower calorific value of the fuel, kJ/kg.

4. Results and discussions

4.1. Optimization of composition

The initial studies on solid fuel block such as optimization of composition, geometry, etc. were confined to single hole sawdust fuel block only. However, in later part, the thermal characteristics were evaluated for both single and multi-hole variety. The optimization study involved a number of trials with different combinations of materials. At the beginning, the fuel blocks were prepared from only biomass, without any oxidizer or binder. However, the blocks were found fragile and the burning was smoky (10 min, smoking period). The smoky operation was thought to be due to fast release of volatile matter due to low packing density. Hence, in order to overcome this difficulty the subsequent trials were made with a new combination i.e. with a mixture of biomass and charcoal powder. Charcoal was chosen because the volatile percentage in charcoal is less than any biomass and hence it was anticipated to reduce the smoking period. Moreover, it was also expected to increase the energy density. Interestingly, the results seemed to be positive in both sense.

As expected, with the above combination, the packing and energy density of the fuel block increased and high packing density resulted in slower burn rate (Fig. 4). The smoking duration was also considerably reduced (5 min), however ignition time increased owing to high packing density. Experiments were done for different compositions of biomass and charcoal powder and finally it has been found that the equal proportion of biomass and charcoal power gives out required thermal power.

The problems of ignition difficulty and inability to hold biomass particle together were solved by addition of oxidizer and binder to the previous combination respectively. Trials were made with two different types of oxidizers viz. potassium nitrate and sodium nitrate and three types of binders (clay, gum arabic, starch). The cost of potassium nitrate was found lower than the cost of sodium nitrate and hence this was chosen for further experiments. It has been found that the fuel block with high percentage of potassium nitrate, the burn rate increased (Fig. 5) and the lower value posed ignition difficulty. Hence, it was necessary to optimize its percent composition. In view of this, a number of trials were made with different proportions and finally 5% found to suffice the requirement.

Among the selected group of binders, clay was chosen as it was found to provide twofold benefits: (i) smokeless operation (ii)

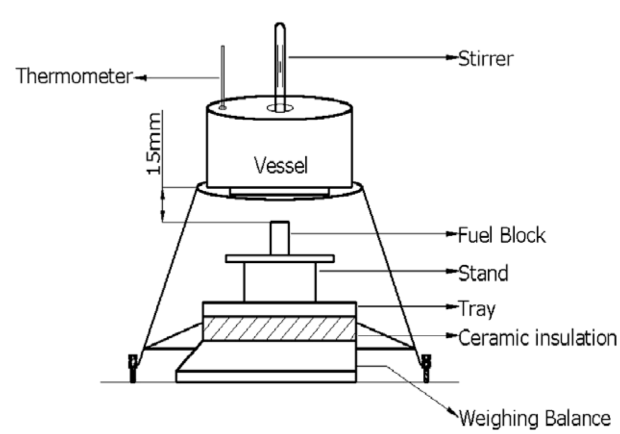

Fig. 3. Experimental setup for thermal efficiency test.

increased packing density with extension of burn duration. Fig. 5 clearly indicates the effects of clay on burn duration. Higher the clay percentage (for case where 0% KNO_3) longer was the burn duration. However, increase in clay percentage of the fuel block offsets this benefit. Hence the clay content was restricted to an amount which is just sufficient to make the fuel block sturdy with enough mechanical strength such that it does not rupture during preparation, handling and storage. Gum arabic and starch was not selected because two binders the problem of smoky operation continued. Besides Gum arabic was found quite expensive (Indian National Rupee 150 per kg).

In this way a good number of experiments were done with different combinations of raw materials and finally the following composition was optimized.

$$\text{Biomass} : 40\%, \text{charcoal} : 40\%, \text{clay} : 15\%, KNO_3 : 5\%.$$

The optimization aimed at operation of fuel block with required ignition time, thermal power and burn duration.

4.2. Optimization of geometry

For test purpose, a number of fuels blocks with 1, 3, 6, 9 and 13 hole were constructed. The aspect ratio (defined as ratio of height-to-hole diameter of the fuel block) was maintained between 4 and 5 for all the configurations. In this range the block was found to operate in gasification mode. The thermal power and burn duration were evaluated for all the cases. Fuel block with single hole (hole diameter 13 mm and 60 mm height) was found to suffice the requirement of barbecuing. And for cooking, 13 hole fuel block (20 mm hole diameter and 94 mm height) met the requirement of cooking in terms of power and total burn time. Table 3 includes the optimized parameters of fuel block for barbecuing and cooking. The designed 3, 6 and 9 hole fuel block met neither the requirement of barbecuing nor cooking. Hence, in this paper there will be no further discussion about these configurations of the fuel

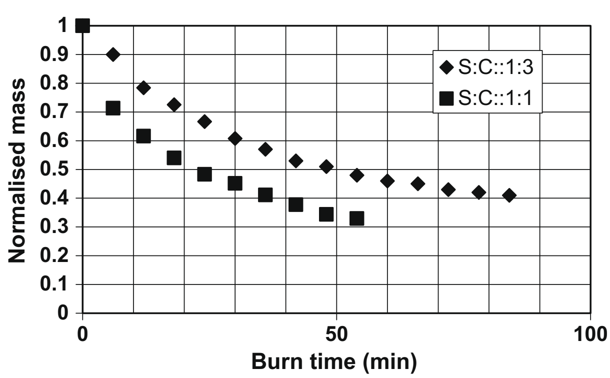

Fig. 4. Effect of charcoal on burn time (S, C represents sawdust and charcoal, respectively).

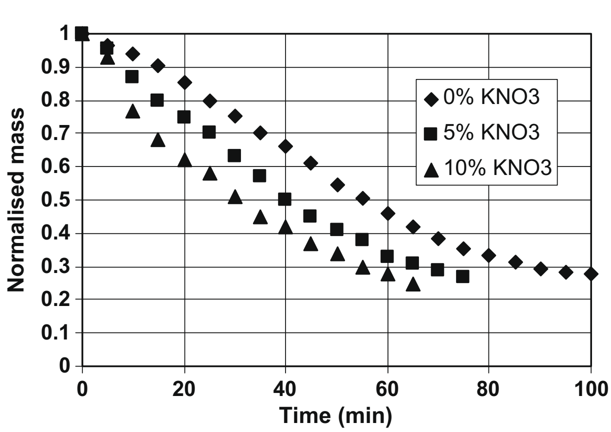

Fig. 5. Effect of oxidizer and binder on burn time.

Table 3
Optimum parameters of fuel block for barbecuing and cooking.

Parameter	Single hole	Multi-hole
Ash (%)	28–30	
Density (kg/m3)	550–600	
Size (mm)	47 dia × 60 height	156 dia × 94 height
Hole dia (mm)	13	20
Holes	1	13
Weight (g)	50–60	700–800
Mean thermal output (kW_{th})	0.13–0.22	1.5–2.0
Burn time (min)	50–60	80–90

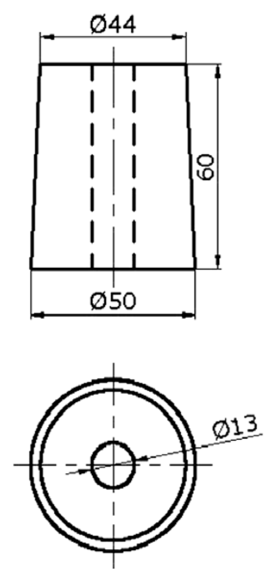

Fig. 6a. Single hole fuel block.

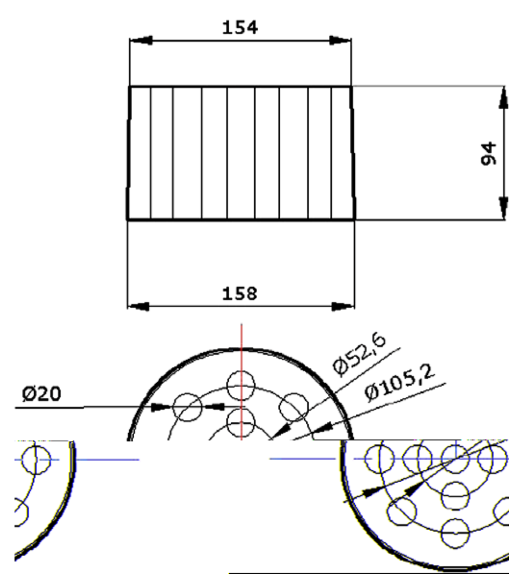

Fig. 6b. Multi-hole fuel block.

Table 4
Performance of the fuel block made of different biomass.

Fuel	Mass of fuel block (g)	Mass of ash left (g)	Mass of fuel consumed (g)	Ignition time (min)	Burn duration (min)	Av. burn rate (g/min)	Av. thermal power (kW)
Sawdust	50	14	36	~2	51	0.7	0.18
Coir pith	40	11	29	~1	42	0.69	0.17
Lucaena leaves	42	15	27	~2	45	0.60	0.14
Bamboo leaves	45	15	30	~5	57	0.52	0.12
Sawdust	700	200	500	~2	80	6.2	1.6

Table 5
Thermal performance of multi-hole fuel block.

Fuel	Water taken (kg)	Fuel consumed (g)	Boiling time (min)	Thermal efficiency (%)
Sawdust	2.5	100	16	46.2
Sawdust	6	184	29	58.0
Sawdust	10	340	55	51.7

block. Fig. 6a shows a single hole and Fig. 6b multi-hole configuration of the optimized fuel block.

4.3. Thermal behavior of the fuel block

The optimized fuel blocks for barbecuing and cooking as illustrated in Fig. 5 were ignited with the help of kerosene. The start up time was as short as 2 min and the flame stabilization took about 5 min. The average thermal power for both single and multi-hole (13 hole) fuel block are listed in Table 4. In this parametric study, sawdust showed better performance in terms of burn duration and thermal power. The burn rate of coir pith was similar to sawdust but with burn duration shorter, this is attributed to lower bulk density of coir pith. Bamboo leaves and Lucaena leaves exhibited lower burn rate than sawdust fuel block. This behavior is attributed to higher ash content. Therefore the thermal power of fuel block made of leafy waste is lower than the fuel block of agro waste and this is due to the low volatile release rate [2]. Thus, to meet performance criteria of a particular power level, the size of the fuel block made of leafy waste should appropriately identified.

It is to be noted that the single hole fuel blocks were constructed from all the selected biomass listed above; however due to the limited resources of other biomass, the study on multi-hole fuel block were confined to sawdust only. Hence, the results of thermal efficiency and average thermal power of 13 hole block are reported for sawdust fuel block only. The thermal efficiency of the 13 hole fuel block was determined at a thermal power of 1.6 kW for three vessels viz. 2.5 kg, 6 kg, 10 kg water capacity. With each of the vessels, the experiments were repeated thrice. The results are summarized in Table 5. It is seen that at one end, the thermal efficiency using 2.5 l vessel was notably low (46.2%). This is found due to lower vessel diameter (diameter: 160 mm, height: 100 mm) for the given fuel block size (156 mm), resulting in lower surface area for heat transfer. Whereas, the 10 l vessel (diameter: 320 mm, height: 175 mm) even though recorded higher efficiency (51.7%) was found unsuitable as the time required to rise the temperature of water was high (55 min). In comparison to these two vessels, the 6 l vessel (diameter: 260 mm, height: 140 mm) was found to be optimal (time required to raise the water temperature was 29 min), which recorded a maximum thermal efficiency of 58%.

5. Economy

Along with the performance evaluation of the solid fuel block, this research also aimed at economic studies. Hence, a very preliminary cost analysis of the optimized fuel block has been carried out. Based on the market price of each raw material, the approximate cost of the designed fuel block was determined. Table 6 shows a comparison of the energy cost of different fuels. Considering the calorific value and consumption in an hour the energy cost is evaluated. Under these considerations the fuel block is found cost effective compared to conventional fuels.

6. Measurement uncertainties

The uncertainty associated with moisture and ash measurement is 0.5%, power measurement is 1% and for thermal efficiency it is believed to be within 2%. The uncertainties were calculated using sequential perturbation technique [16].

7. Conclusions and recommendations

A highly densified fuel block for cooking and barbecuing has been developed from low cost agro residues. An attempt was made in optimizing the geometry and composition of the fuel block for the best thermal performance. Thermal power and thermal efficiency were evaluated for different fuel blocks. The study can be summarized as follows:

1. Cost effective fuel block can be prepared from a range of agro residues. The optimum mixture composition which gives the best result in terms of performance and economy is Biomass: 40%, charcoal: 40%, clay: 15%, KNO_3: 5%.
2. It can be designed in such a way that it meets the end use requirement. Hole size and hole numbers are identified as the controlling parameter for thermal power.
3. Single and 13 hole fuel block are suitable for barbecuing and cooking respectively.
4. The maximum thermal efficiency obtained for 13 hole fuel block sawdust fuel block was 58% at 1.6 kW_{th} mean thermal power.

Table 6
Cost analysis.

Fuel	Lower calorific value (MJ/kg)	Cost per kg of fuel (Rs)	Cost of one MJ energy (INR/MJ)	Fuel consumption rate (kg/hr)	Energy consumption in 1 h (MJ)	Energy cost (INR)
LPG[a]	46	22	0.47	0.140	6.4	3.0
Kerosene [a]	44	22	0.5	0.200	8.8	4.4
Fuel block[b]	16	3.5	0.21	0.700	11.2	2.3

[a] Market price of fuel in Indian Rupees (INR).
[b] Price of fuel block considering only raw material cost.

5. Energy cost of the fuel block is comparable to high grade fuels like LPG, kerosene.

Since the preliminary results are very encouraging one, experiments are being planned to have a thorough study of thermal performance of all kinds of solid fuel block (not only saw dust) in near future. The investigation will mainly focus on emission, efficiencies and heat transfer characteristics of the solid fuel block.

Acknowledgments

The author Ms. Monikankana Sharma would like to thank Ministry of New and Renewable Energy, India for providing National Renewable Energy Fellowship during M. Tech to carry out this work.

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