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Thermal performance of three improved biomass-fired cookstoves using fuel wood, wood pellets and coconut shell

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Abstract India produces 500 million metric tones of renewable agricultural biomass every year, primarily used as a cooking fuel. Inefficient combustion of biomass is one of the major hindrances for the effective utilization of this vast reserve of energy. Inefficient combustion may occur due to several factors such as lack of proper air circulation, improper packing of fuel and excess moisture content in the fuel. This paper describes the performance evaluation of three improved stoves; natural draft TLUD stove and forced draft Purti and Mpurti stove using three kinds of biomass fuel as wood chips, wood pellets and coconut shell. It was found that the thermal efficiency of the natural draft TLUD stove was 26–27%, electric fan operated Purti stove was 44–45%, and solar fan operated Mpurti stove was 46–48%. This performance was assessed by the standard laboratory-based water boiling test method (WBT) to get thermal efficiency, burning rate, boiling point, specific fuel consumption and firepower. The economic analysis study was carried out to get an idea about the approximate cost that would be incurred per month on the fuel. All these desirable parameters are maximized for the efficient combustion of fuel. The gaseous components like CO and CO_2 obtained over the fuel bed are analyzed using gas chromatography. Particulate matter ($PM_{2.5}$) was measured by the fine particulate sampler. $PM_{2.5}$ concentration for traditional cookstoves was much higher than studied forced draft Mpurti ($510 \pm 45\ \mu g/m^3$) and Purti stove ($677 \pm 40\ \mu g/m^3$). The reduction in the indoor concentration of $PM_{2.5}$ for Mpurti is about 60–63% as compared to traditional stove. Mean CO emissions on a volumetric basis during the cold start and hot start phase were lowest for Mpurti forced draft stove (2.41%). The study reveals that clean cooking can be achieved using the forced draft Mpurti stove.

Keywords Cookstoves · Forced draft · Specific fuel consumption · Thermal efficiency

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Abbreviations

h_c	Thermal efficiency of the stove (%)
Pj_{ci}	Mass of container of water before test (g)
Pj	Weight of empty container (g)
Tj	Temperature of water before test (°C)
Tj_{ci}	Water temperature at start of test (°C)
W_{cv}	Quantity of water evaporated (g)
f_{cd}	Equivalent mass of fuel consumed (g)
LHV	Lower heating value
SC_c	Specific fuel consumption (g of fuel/g of water)
Pj_{cf}	Mass of container of water after test (g)
T_b	Local boiling point of water (°C)
Δt_s	Time to boil (min)
WP	Wood pellets
WC	Wood chips
CS	Coconut shells
FP_s	Fire power (Watt)
BR	Burning rate (g/min)
WPBD	Wood pellets bone dry
CSBD	Coconut shells bone dry
WCBD	Wood chips bone dry

1 Introduction

Modern LPG cylinders which are ubiquitous in most of the urban areas are still not accessible to a large chunk of the population in the rural areas. These people still depend heavily on biomass to meet their household cooking energy requirements. There are 34 countries where woodfuel provide more than 70% of their energy needs (Mead 2001). The demand of woodfuel will remain strong for many years to come due to its higher energy density as compared to other biomass and convenience in use and transportation. In India, the available biomass is primarily used as a fuel for cooking food by its combustion either in conventional open fire or in biomass gasifier stoves. Combustion in traditional cookstoves in an open flame is not controlled, and it results in the production of smoke and various harmful gases, for example, carbon monoxide (CO), carbon dioxide (CO_2) and particulate matter ($PM_{2.5}$). Gasifier stoves are considered as cleaner cooking in comparison with traditional cookstoves because of its efficient and clean utilization of the fuel. The efficient utilization of fuel depends on a range of factors such as its type, its moisture content and stove design-dependent parameters such as fuel bed space for air circulation and height to diameter ratio.

The numerous studies on improved cookstoves (ICS) developed across the world can be classified on the basis of configuration material and mode of biomass combustion. These stoves are designed to maximize thermal and fuel efficiency, lower emissions, better safety, enhanced durability and heat reduction to make cookstove more efficient. The conflicting trends in efficiency versus power by Prasad et al. (1985) designated power levels as a significant factor in establishing a cookstoves performance. Different power levels lead to very different thermal efficiencies, and therefore, it is crucial to understand the range of power levels that exist during field conditions. Jetter et al. (2012) proposed that the specific fuel consumption (SFC) to be reported based on the task performed rather than fuel consumed. Both the features are incorporated in the present study.

Some researchers including Reed and Larson (1996) built a fan-based stove, but it was economically unreasonable, partly due to the high-priced of the fan and the power to operate the fan; Witt (2005) performed studies on fan stoves, indicates an average reduction in fuel use by 40%; Mukhopadhyay et al. (2012), Mukunda et al. (2010) and Jetter et al. (2012) discussed the energy efficiency and field outreach of fan stoves. Since the improved cookstoves were developed during the fuel crisis period, keeping in mind the end goal to contribute toward fuel saving therefore, cookstoves designers fail to notice the gaps in these cookstoves that were responsible for emission of pollutants (Arora and Jain 2016). Different studies show that there is much scope for improvements in cookstove emission. Table 1 represents different stove studies in emissions inventories, which include emission factors as a mass of species emitted per unit mass of dry fuel consumed for CO and $PM_{2.5}$ with mean values for each stove. It also contains information on the stove comparison of tests, place of test and approximate cost.

Based on above anomalies, the objectives of this study were to analyze and compare stoves on the parameters such as thermal efficiency, specific fuel consumption, burning rate, fire power and concentration of pollutants such as CO, CO_2 and $PM_{2.5}$ using fuels like wood chips, wood pellets and coconut shell. The performance of three gasifier stoves, namely TLUD stove, Purti and Mpurti cookstoves, was evaluated on the basis of experimental data with aim to improve the combustion quality with less heat loss. A study led to a wide range of understanding of the gasification and combustion behavior of fuel on the top lid updraft stove and forced draft stoves. Results are more descriptive about the performance behavior of fuel with respect to fan-based rectangular-shaped cookstove which is rarely to be seen design in cooking operation. It has also led to the development of parameters for getting high efficiency and low emissions from stoves. The results of the evaluation also throw light on certain areas such as, economic analysis of stove, heat loss due to conduction, convection and radiation, selection of fuel, design aspects, air to fuel ratio.

2 Materials and methods

2.1 Biomass fuel used in the study and their characteristics

Three stoves were tested using wood chips, wood pellets and coconut shells. As shown in Table 2, the size of wood pellets is small, i.e., of 8 mm diameter and approximately 3–4 cm in length. Smaller wood pellets have the highest resistance to air flow, and it is better for cookstoves (Li 1994). The wood pellets have a density of 796 kg/m^3 higher than wood chips of 656 kg/m^3 and coconut shell of 239 kg/m^3; moreover, wood pellets are uniform in density and have good structural strength. Also, wood pellets have high value in bulk density of 588 kg/m^3, whereas less in wood chips of 385 kg/m^3 and coconut shell of 318 kg/m^3 because of low volumetric energy content. The wood pellets were purchased from the local fuel wood market. The wood chips are the most commonly used fuel available in the village. The pellets have controlled moisture content and higher energy density, which leads to the improvement in its characteristics as a fuel (Stahl et al. 2004). Also, pellets have higher volumetric calorific value as compared to the wood chips and coconut shell. The coconut shell used has the average dimension of 20 mm × 5 mm × 2 mm and a bulk density of 318 kg/m^3. The coconut shell was used as fuel in this study as in India there are

Table 1 Comparative of different cookstoves based on salient features

Sr. no	Stove type	Thermal efficiency (%)	CO emission factors (µg/kg)	PM emission factors (µg/kg)	Types of tests	Testing place	Approx cost Rs.	Reference
1	Three-stone fire	15–19	70	4.1	CCT	Laboratory hood	–	Coffey et al. (2017)
2	Gyapa rocket stove	18	50	2.5	CCT	Laboratory hood	400	Coffey et al. (2017)
3	Philips Wood-4012	36.2	41	2.4	CCT	Laboratory hood	5700	Coffey et al. (2017)
4	Philips charcoal	–	90	2	CCT	Laboratory hood	–	Coffey et al. (2017)
5	Coal pot	17	230	0.25	CCT	Laboratory hood	–	Coffey et al. (2017)
6	Three-stone fire	19	51	3.5	WBT	Kitchen	–	Still et al. (2011)
7	Mud/Saw dust	28	43	5.1	WBT	Kitchen	–	Still et al. (2011)
8	VITA	29	93	8.3	WBT	Kitchen	150	Still et al. (2011)
9	Envirofit G-3300 stove	38	2.094 (g/l)	189.5 (mg/l)	WBT	Laboratory	2015	Jetter et al. (2012)
10	Oorja	32.1	1.03 (g/l)	61.8 (mg/lit)	WBT	Laboratory	2275	Jetter et al. (2012)
11	Mayon turbo stove 7000	29.3	6.299 (g/l)	237.4 (mg/l)	WBT	Laboratory	975	Jetter et al. (2012)
12	Wood gas fan stove	45	0.549 (g/l)	2.2 (mg/l)	WBT	Laboratory	6435	Jetter et al. (2012)

CCT controlled cooking test, *WBT* water boiling test

Table 2 Ultimate and proximate analysis of fuel used for the TLUD, Purti and Mpurti stoves

Fuel	Wood chips	Wood pellets	Coconut shells
Density (kg/m^3)	656	796	239
Dimensions (mm)	Length 50 Breadth 20 Height 20	Diameter 8 Length 40–30	Length 20 Breadth 5 Height 2
Bulk density(kg/m^3)	385	588	318
% Ultimate analysis wt. (%)			
Carbon	44.23	42.31	49.41
Hydrogen	6.56	6.53	6.20
Nitrogen	0.21	3.80	0.28
Oxygen	49	47.37	44.11
% Proximate analysis wt. (%)			
Moisture	3.8	4.3	5.60
Volatile	76.86	89.43	71.84
Fixed carbon	15.59	1.14	22.09
Ash content	3.74	5.12	0.47

many states where the coconut shells can be easily available and can be a better option as fuel.

The proximate analysis of wood chips, wood pellets and coconut shells was carried out before the water boiling test using the method suggested by the annual book of ASTM Standard Philadelphia (1983) which includes for moisture content take 1 g of finely powdered air dried wood sample in pre-weighed silica crucible. The crucible was placed inside an electric hot air oven, maintained at 105–110 °C. The crucible was allowed to remain in oven for 1 h and then taken out with the help of a pair of tongs, cooled in a desiccator and weighed. Then the loss in weight was reported as moisture content. The volatiles in fuel are found out by taking 1 g initial weight of biomass taken in pre-weighed silica crucible. The silica crucible was covered with an aluminum foil lid. This crucible was placed in the furnace with temperature (920 °C ± 20) for 7 min. The ash content of fuel is found by taking of 1 g of fuel sample in pre-weighed silica crucible. It is heated in a muffle furnace without lid to 500 °C in 30 min. Further, the temperature is increased to 815 °C maintained at this temperature until a constant mass is reached. This mass is nothing but the ash content of fuel. An ultimate analysis is carried out by using CHNS-O elemental analyzer. Both these analyses are given in Table 2.

2.2 Burning rate test

The burning rate test gives the time for which stove can be used for heating purpose with the given quantity of fuel. It actually gives the exact time in which the fuel fed to the stove gets consumed and it also gives the idea of the suitability of the biomass fuel used. This test also gives details about the flaming mode and char mode of the fuel used. The results of the burning rate test give the burn rate of the fuel used in the particular stove and time for which the stove operates. This time is then used to calculate cooking power of the stove (Bhattacharya et al. 2002). In the present study, this test is carried out for three different biomasses: wood pellets bone dry (WPBD), coconut shells bone dry (CSBD) and wood

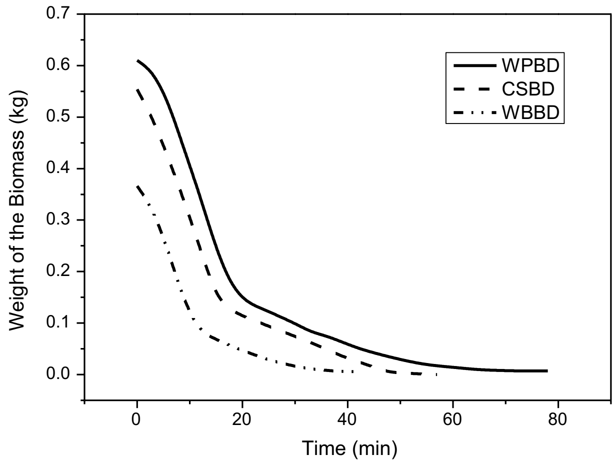
Chips bone dry (WCBD). To obtain bone dry wood pellets, normal wood pellets are set aside in an oven at 105 °C for 2 days and then used in the experiments.

Moisture content is determined by heating the biomass sample at 105–110 °C under specified conditions until a constant weight is obtained. As shown in Table 2, results of coconut shell imply higher moisture content 5.06% and fixed carbon 22.09% as compared to wood chips and wood pellets. The fixed-carbon content of a fuel is determined by subtracting the percentages of moisture, volatile matter, and ash from a sample. Volatile matter is material that is driven off when the fuel sample is heated to 950 °C in the absence of air under specified conditions. It is measured practically by determining the loss of weight. In general, fuel with high volatile-matter ignite easily and are highly reactive in combustion applications. As shown in Table 2, the volatile matter in wood pellets (89.43%) is higher as compared to wood chips (76.86%) and coconut shells (71.84%). The ultimate analysis indicates the various elemental chemical constituents such as carbon, hydrogen, nitrogen, sulfur, etc., present in the fuel. This information is required for the calculation of flame temperature, quantity of air required for combustion and the flue duct design. The procedure for conducting this test is as given below:

- A fixed quantity of the fuel is measured and filled into the stove. Few drops of kerosene are also added to the fuel to act as a starter.
- The stove is then placed on the weighing machine, and the weight indicated by the machine is noted.
- The stove is then ignited, and the stopwatch is started.
- The variation in the weight of the stove after every three minutes is noted till the complete fuel is consumed.
- Burn rate is then calculated by dividing the mass of the fuel by the total time required for its consumption.

From Fig. 1, it is seen that all the fuels are completely consumed in the tests. These results are found to be consistent with the report of Varunkumar et al. (2011a, b). Wood pellets were observed to be better as compared to other fuels due to more burning time up to 78 min.

Fig. 1 Comparison of burning rate curve for different fuel in Purti stove



2.3 Experimental procedure

2.3.1 Stove

2.3.1.1 TLUD stove The majority of the gasifier cookstoves have been developed are making use of the TLUD (Top Lit Updraft) design. In the TLUD design, biomass fuel is batch fed into the fuel chamber and is ignited from the top. Fuel consumption proceeds in the downward direction. There are many designs of TLUD in the recent literature, large TLUD stove equipped with a chimney riser and pot skirt popular stove chimney types include 'Uganda 2-pot' (Uganda) stove made by clay. It is squat and rectangular, and a couple of pots sits on top. 'Patsari' (Mexico) is squat stove which is usually built from brick, it has three burners, one large and two small, provided with chimney to keep smoke and soot out. 'Justa' stove is built from bricks or blocks of concrete or adobe. This stove has a top with one large metal griddle, for cooking. It has a combustion chamber for wood, as well as a chimney for ventilation. 'Ecostove' made from inexpensive ceramic floor tile called baldosa can be molded to give shape to the combustion chamber. Loose insulation filled inside between the combustion chamber and inside of the stove body to minimize the risk of burns to small children. 'Onil' (Guatemala) stove is feathered with clay-fired insulated chamber, durable, sits off the floor that can reduce the heat burning. The stove vented by a galvanized steel chimney (Still et al. 2011) and smaller TLUD stove without a chimney (Tryner et al. 2013) was based on an open source natural draft semi-gasifier design (Wendelbo 2012). Our studied TLUD stove design as shown in Fig. 2 is constructed using two concentric cylinders having a difference of more than 6 cm in their diameters. The outer cylinder supports the inner fuel chamber. It is approximately 10–15 mm above the bottom of the unit to minimize any problems of heat energy from the inner chamber radiating down and damaging the surface on which the unit is placed during its operation. It also prevents direct exposure of the hot inner fuel chamber to minimize burns in case of contact. The cylinders are attached to each other in a way that the top of inner cylinder of diameter 17.5 cm is at a lower height than the top of the outer cylinder of 22 cm in diameter with stove length of 24 cm; hence, L/D ratio is 1.6. The inner cylinder has a mesh structure at its bottom which acts as a secondary air inlet, while the tube hole on the side acts as the primary air inlet having a diameter of 7 cm. The outer cylinder also takes in air from the gap provided below the tube hole cylinder. Any biomass having humidity less than 20% can be used as fuel, filled up to the neck of the inner cylinder. Initially, the top layer of the fuel is ignited. Air enters via primary and secondary air inlets. The primary inlet helps in the upward draft lifting of the gasified biomass, and the secondary inlet below the fuel layer helps in gasification of the biomass.

2.3.1.2 Purti stove The Purti stove is manufactured and marketed by Purti Alternative Fuels Pvt. Ltd. on a commercial scale. This is a forced draft stove with the inbuilt fan arrangement. The stove contains coaxial rectangular chambers of height 260 mm as shown in Fig. 3, both made from cast iron. The inner chamber contains an iron grate on which the fuel rests and it also ensures the continuous removal of ash which is collected at the bottom. The fan sucks in the air in a hollow compartment which is then circulated through six air holes of 6 mm diameter each provided on the inner top end of the compartment.

2.3.1.3 Mpurti stove The Mpurti stove is the modification of Purti stove. It is designed and fabricated to include the solar based fans at relatively low price. Solar system stores amount of energy into the battery which is then used to run the fan. The stove contains coaxial rec-

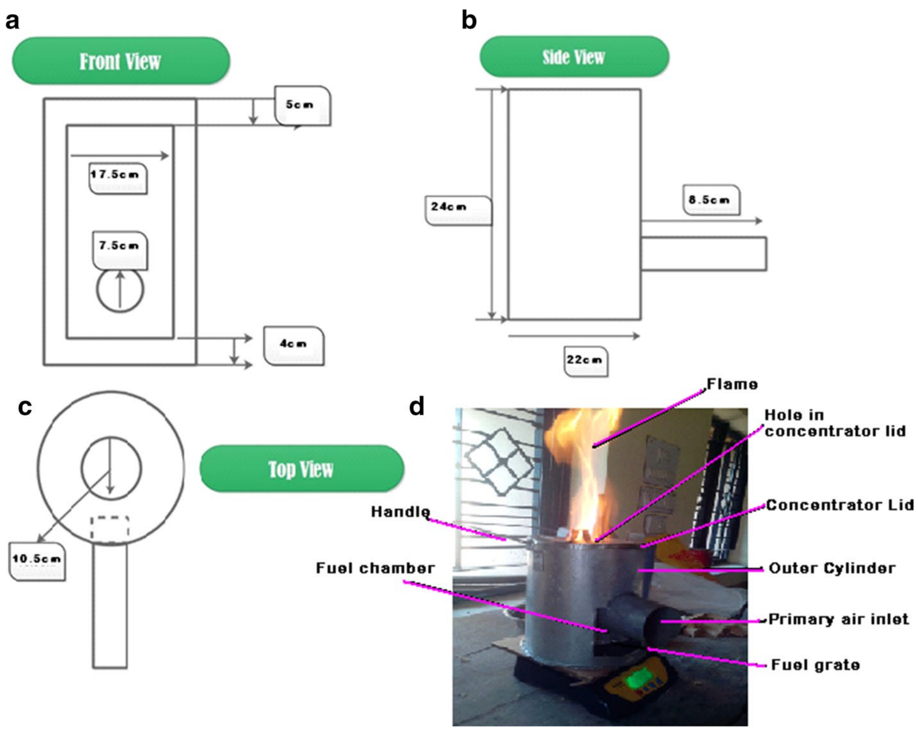


Fig. 2 Schematic of (**a**) TLUD stove front view with all dimensions in cm (**b**) TLUD stove side view with cross section (**c**) TLUD stove top (with lid) view (**d**) The TLUD stove

tangular chambers made from cast iron as shown in Fig. 4. The inner chamber ceramic tiles are fixed to all four sides of the combustion chamber. This lightweight insulating ceramic material helps to increase the heat for a long time in the combustion chamber and to promote complete combustion. An iron grate on which the fuel rests ensures the continuous removal of ash, which is collected at the bottom. The fan sucks in the air in a hollow compartment which is then circulated through air holes provided on the inner top end of the compartment.

2.3.2 Measuring concentration of gases and particles during the experiments

2.3.2.1 Measurement of $PM_{2.5}$ and exhaust gases $PM_{2.5}$ is fine particles that are smaller in diameter or in size 2.5 micrometers (μm). It is measured from ambient air near the experimental setup. The measurement of $PM_{2.5}$ was conducted with an electrically powered air sampler which draws ambient air at a constant volumetric flow rate of 22–24 m^3/day (Model: Envirotechinsts (P) LTD APM 550 Fine Particulate Sampler, New Delhi). The $PM_{2.5}$ was collected using a 47-mm-diameter Teflon (PTFE) filter paper with polypropylene support ring. It is needed to take weight for each filter before and after sample collection to determine the net gain due to the particulate matter. The air was drawn through the cyclone pre-selectors by electrical operated constant flow sampling pump. Before and after each set of sampling, the air flow from the pump was calibrated with the help of rotameter. Prior to weighing, the sample filters need to be equilibrated for a minimum of 24 h in a controlled

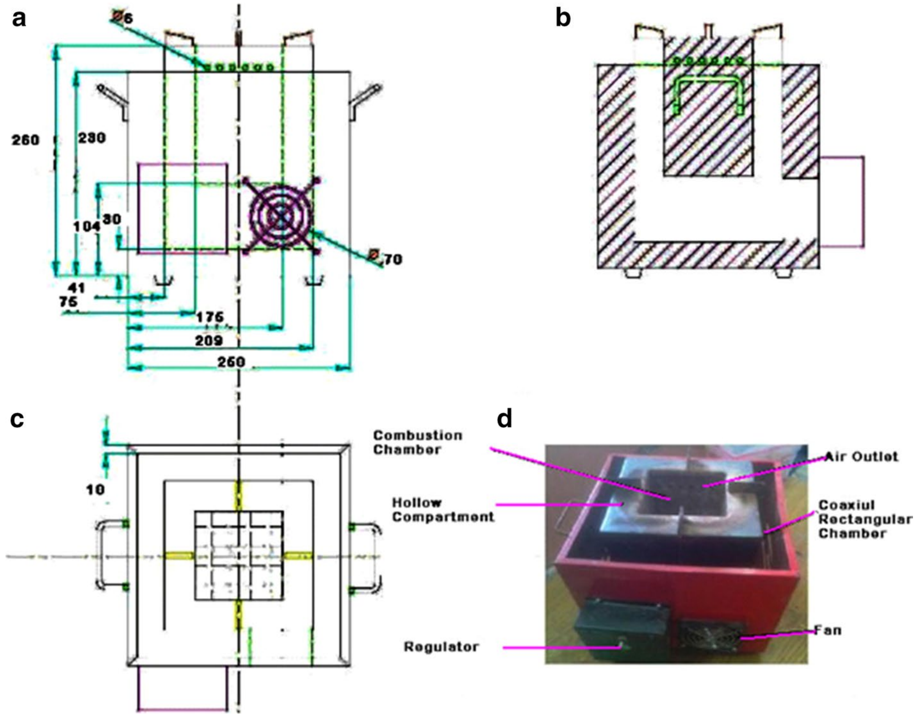


Fig. 3 Schematic of (**a**) Purti stove side view with all dimensions in mm (**b**) Purti stove side view with cross section (**c**) Purti stove top view (**d**) the Purti stove

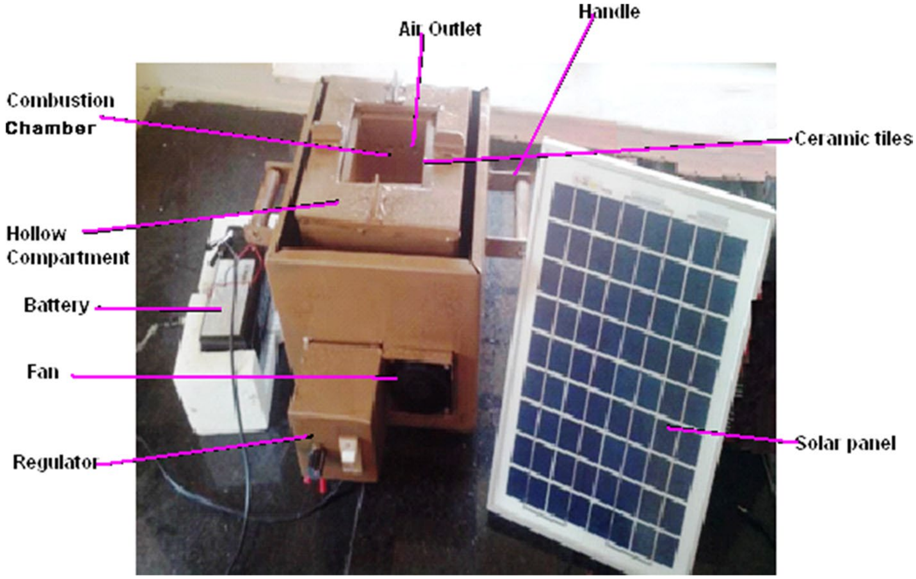


Fig. 4 MPurti stove

environment. The mass concentration in the ambient air was computed after sampling is done for 24 h. The mass concentration in the ambient air was computed after sampling is done for 24 h as the total mass of collected particles in the $PM_{2.5}$ size ranges divided by the actual volume of air sampled, and is expressed in μg/m^3.

The system of gas collection as shown in Fig. 5 is required for the collection of gas in Tedlar bags at the time of the water boiling test. Funnel with upside down is fixed over the stove at distance of 1 m from the edge of the combustion zone, and the exhaust gas is sucked using peristaltic pump and passed through a silicon tube of inner diameter of 3–4 mm with the required flow rate of 30-45 ml/min at 160 rpm. Further, these gases are collected in the Tedlar bag of 1 l capacity. Gas chromatography (Shimadzu GC-2014) is used to analyze the composition in this major component involved. The carrier helium gas led at a constant flow rate of 25 ml/min is fitted with injectors which is used to provide a constant volume of 1 μl injection of the sample into the carrier gas stream. Columns used in GC as Molecular Sieve-5A of length of 2 m stainless steel with diameter 1/8 inch. Column oven maintains constant temperature 50 °C. The detector used is a thermal conductivity detector which is kept at temperature of 140 °C which provides specific response for the separated components like hydrogen, methane, carbon monoxide. Column Porapak Q is used to analyze the components of carbon dioxide with above same conditions of gas chromatography. The concentrations of CO and CO_2 in the laboratory were measured continuously throughout the water boiling test for all three stoves using three different solid biomass fuels.

2.3.2.2 Water boiling test The water boiling test is a relatively short and simple simulation of the common cooking procedure. This test is used to measure the efficiency of the stove to heat the 2-kg quantity of water and quantity of emission during cooking by using biomass. The three phases in the water boiling test include: high-power (cold start) phase, high-power

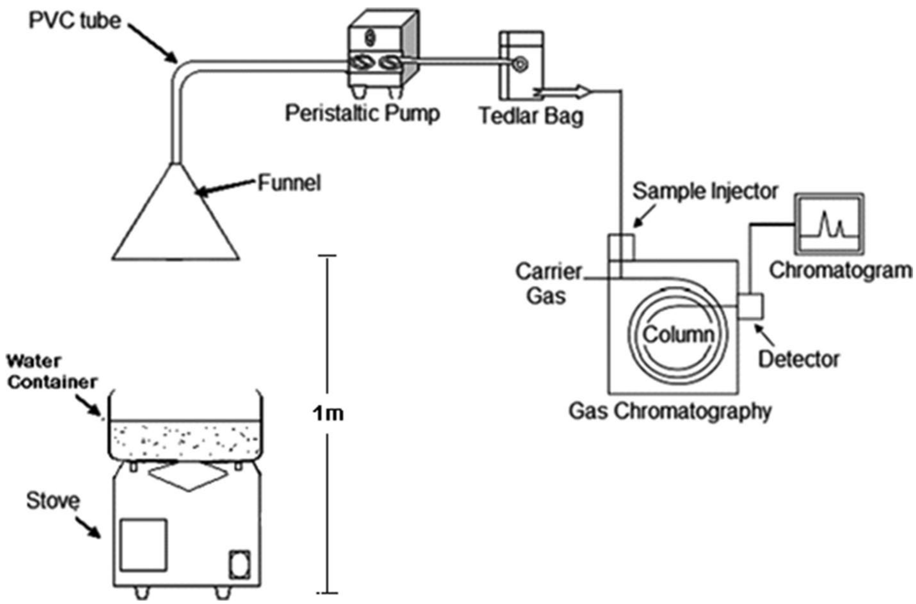


Fig. 5 Schematic diagram of equipment setup for measurement of exhaust gases

(hot start) phase and low-power (simmer) phase. Each of these tests was repeated for four times to rule out any experimental errors. This test was performed under controlled indoors conditions with wind protection and sufficient ventilation.

2.3.2.3 High-power cold start phase In the first phase, the stove was operated with different fuels to get its performance with respect to the fuel used. The stove is fully loaded with 600 g of wood fuel (same weight is taken for other fuel), and kerosene is used as fire starter. 2.0 kg of water was made to boil in a standard aluminum pot of 30 cm diameter without lid, starting with the stove at room temperature. The room temperature and the initial temperature of water in the container were recorded. The measured quantity of wood pellets was loaded into the cookstove, and a few drops of kerosene were also added to the fuel to act as a starter. The stove is then placed on the weighing machine, and the weight indicated by the machine is noted at an interval of 5 min till the water reaches boiling point. The final temperature of water was recorded at boiling point. The pot was then removed from the stove, and individual weight of water container was recorded. The unburned wood pellets left after burning was weighed to determine the amount of fuel consumed during the test period.

2.3.2.4 High-power hot start phase The high-power hot start follows immediately after the first test, while the stove is still hot. This test was conducted just after the cold start test. It is required to remove the water container and pour 2 kg fresh water and 600 g of wood pellets in the stove. The same procedure is repeated as in the cold start test. Both tests helped to identify differences in performance between all three stoves.

2.3.2.5 Low-power simmering phase Low-power simmering phase means to simmer water with minimum fuel. This test followed immediately after the second test. The test determines the amount of fuel required to simmer a measured amount of water at just below boiling for 45 min. In this test, the given aluminum pot was filled with 2 kg of fresh water. The original temperature of the water at room temperature was recorded, and the same procedure to test the water boil was followed. The temperature and the boiling water time were recorded. The pots with the boiled water were weighed and quickly returned to the stoves. The remaining part of the pre-weighed 1 kg of fuel wood pellets was weighed, and the fires of the stove were reduced to keep the water as close to 3 °C below the boiling point as possible. These fires maintain for 45 min, and at the end the temperature of the water in the pot was recorded. The remaining fuel wood pellets removed from the TLUD stove the unused wood pellets from the pre-weighed bundle were weighed. The pot with the remaining quantity of water was weighted. The loose charcoal knocked off from the fuel wood pellets together with the ones removed from the TLUD stove was weighted. The same process repeated for another two different fuel coconut shell and wood chips for Mpurti and Purti cookstoves. The experiment is replicated four times on each fuel. With the data collected, thermal efficiency, specific fuel consumption, fire power, boiling time and burning rate are calculated as thermal performance indicators by Eqs. (1–4) reported by Bailis et al. (2007).

$$h_c = \frac{\left[4.186 * \sum_{j=1}^{4} (\mathrm{Pj_{ci}} - \mathrm{Pj})\right] + 2260 * (W_{\mathrm{cv}})}{f_{\mathrm{cd}} * \mathrm{LHV}} \quad (1)$$

$$\mathrm{SC_c} = \frac{f_{\mathrm{cd}}}{\sum_{j=1}^{4} \left[(\mathrm{Pj_{cf}} - \mathrm{Pj}) * \frac{(\mathrm{Tj_{cf}} - \mathrm{Tj_{ci}})}{T_{\mathrm{b}} - \mathrm{Tj_{ci}}}\right]} \quad (2)$$

$$FP_s = \frac{f_{cd} * LHV}{\Delta t_s * 60} \tag{3}$$

$$BR = \frac{f_{cd}}{\Delta t_s} \tag{4}$$

2.4 Limitations of the water boiling test

The water boiling test was carried out to evaluate stove performance in a controlled way, and thus, it is probably less like a local cooking test. In spite of the fact that the WBT is a helpful tool for the reasons given over, it is important to talk about its limitations. It is an estimate of the cooking procedure and is directed in controlled conditions via trained experts. Research laboratory test results may contrast, when cooking normal food with local fuels. In WBT it is difficult to know to demonstrate the effect of stove interventions on household fuel consumption. In laboratory kind WBT we are not getting the qualitative aspect of stove performance. An economy of scales between fuel consumption and the number of people served cannot be identified in larger households. It is also the most difficult way to test stoves because it cannot include people's daily activities.

2.5 Flaming and char mode

The two phases in consumption of biomass are flaming mode and char mode. Flaming mode involves the main combustion stage where the biomass is rapidly consumed to release carbon dioxide, energy and other emissions and then converted into char as represented in Eq. (5). The equation for char mode is represented by Eq. (6). Varunkumar et al. (2011a, b) in their study reported that in the char mode as the fuel consumed up to the grate, all biomass is de-volatilized and on the grate about 10–11% of hot char is left. The air coming in through the grate causes surface oxidation of char and generates primarily CO and CO_2 and little H_2. CO_2 so generated passes through the hot char on top and can undergo reduction with carbon to form CO. The conversion process in the char mode is also a part of the gasification process until the last 5% burn time. After this, the amount of char left behind is consumed in a combustion mode and what will be left behind finally was ash. Figure 6 shows the burning rate curve for bone dry wood pellets where flaming mode and char mode of combustion were observed.

The produced biomass gas burns with an orange-blue flame like liquid petroleum gas with a flame temperature of 808 °C. About 2–3% of ash was left for each fuel used after completion of char mode. From the slope of flame mode and char mode, the burning rate of the fuel can be obtained which, when multiplied by the calorific value gives the cooking power of the fuel for both modes. It was seen that the Purti stove offers the significant advantage of complete utilization of fuel. Mass, energy and power levels in the two modes are shown in Table 3. It is clear that flaming mode constituted 80% of total energy consumption. Equations (7) and (8) represent the best fit for flame mode and char mode, respectively, obtained from MS Excel. 'M' indicates the mass of fuel in gram, and 't' represents time in minutes. In Eq. (7) high constant value of 0.553 for flame mode results faster burn rate as compared to the low constant value of 0.089 for char mode Eq. (8). The negative coefficients of 't' in both the equations indicate that mass is decreasing with time.

$$\text{Flame mode : Biomass + Air } H_2O + \text{Char + Gases } \left(CO,\ CO_2 \text{ and } H_2\right) \tag{5}$$

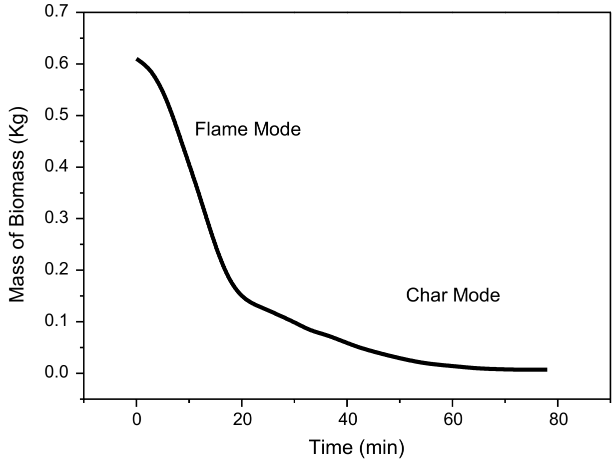


Fig. 6 Burning rate curve for wood pellets bone dry in Purti stove

Table 3 Mass, energy and power behavior of bone dry wood pellets in Purti stove

Mode	Fuel (g)	Burning rate (g/min)	Calorific value (MJ/Kg)	Energy (MJ)	Time (min)	Power (kW)
Flaming	516	9.55	15.7	8.1012	54	2.5
Char	83	3.45	25	2.075	24	1.44

$$\text{Char mode}: \text{Char} + \text{Air Ash} + \text{Gases}\left(CO,\ CO_2 \text{ and } H_2\right) \tag{6}$$

$$M = -0.015t + 0.553,\ R^2 = 0.880 \tag{7}$$

$$M = -0.001t + 0.089,\ R^2 = 0.853 \tag{8}$$

3 Results and discussion

3.1 Variations of different parameters with wood chips, wood pellets and coconut shell

3.1.1 Variation of thermal efficiency

The huge variations in thermal efficiency were seen in the forced draft and natural draft stove. During the hot start phase, high thermal efficiency (46–48%) was found in the Mpurti stove while using all three types of fuel as shown in Table 4. The thermal efficiency during the cold start phase was 45.5, and 26.35% for Purti and TLUD, respectively. From uncertainty analysis the differences between these fuels are statistically significant ($p < 0.05$). Thermal efficiency was also higher for the Mpurti stove as comparable to Oorja stove (32.1%) and Philips HD 4008 stove (34.2%) as mentioned by Jetter et al. (2012). This improvement in efficiency was due to better control of the ratio of primary and secondary

Table 4 Comparison of the results on efficiency, fire power, boiling point and burning rate for various fuels in TLUD, Purti and Mpurti stove

Performance parameters and fuel used		High power (cold start)			High power (hot start)			Low power (simmer)		
		TLUD	Purti	Mpurti	TLUD	Purti	Mpurti	TLUD	Purti	Mpurti
Burning rate (g/min)	WC	14	9	9	15	10	12	8	5.5	9
	WP	13	9	9	15	10	12	9	6	9
	CS	12	8	8	16	9	11	7	5.5	8
Specific fuel consumption (g/l)	WC	0.16	0.126	0.124	0.16	0.123	0.120	0.45	0.36	0.34
	WP	0.15	0.121	0.122	0.16	0.122	0.121	0.46	0.34	0.33
	CS	0.16	0.122	0.123	0.16	0.124	0.124	0.46	0.34	0.34
Thermal efficiency (%)	WC	25	43	44	26	44	46	28.5	36	38
	WP	26	44	46	26	45	48	28	39	39
	CS	27	42	45	27	43	46	29	37	40
Fire power (W)	WC	4277	2660	2641	4519	3157	3545	2557	1623	2672
	WP	4277	2662	2645	4519	3147	3553	2546	1654	2653
	CS	4247	2666	2642	4519	3153	3533	2529	1623	2674
Boiling point (min)	WC	15	16.5	16	14.5	13	11.5	–	–	–
	WP	15.5	16	16	14	13	11	–	–	–
	CS	16	16	16	14	13.5	11	–	–	–

air, as well as control of the gross air supply in both studied forced draft stoves. In addition to that ceramic tile reduces the conduction of heat as compared to the conduction occur in metallic Purti stove and TLUD stove. It was observed that the improvement in the efficiency compared with traditional chulhas (Suresh et al. 2016; Bailis et al. 2007) of cookstoves was in the range of 25–29% which contributes a significant reduction in fuel consumption. The thermal efficiency was found to be higher for wood pellets (WP) and coconut shells (CS) in both Mpurti and Purti stoves as compared to wood chips (WC).

3.1.2 Variation of boiling point

Boiling point time (BP) is the time at which the boiling starts. Boiling point time was found to decrease from natural draft TLUD to forced draft stove Mpurti stove in hot start phase. The average value of boiling point time in of TLUD, Purti and Mpurti stoves is found to be 14, 13 and 11 min, respectively, for all fuel consider for study. The boiling point time in cold start phase is found to be nearly similar to within 15–16 min for all stoves consider for study. The fuel consumption to reach boiling point is less in forced draft stoves as compared to natural draft stove. The fuel consumption is 137 and 141 g in Mpurti and Purti stoves, respectively, as compared to 198 g in TLUD stove. In Mpurti stove, the presence of ceramic tiles in the combustion chamber walls is responsible for net gain in energy and less heat loss during the combustion and hence less fuel consumption.

3.1.3 Variation of specific fuel consumption

The specific fuel consumption is a measure of the amount of fuel required to boil (or simmer) 1 l of water. It is calculated by subtracting the dry fuel used in the remaining charcoal divided by the amount of water (l) remaining at the end of the test. In this way, the fuel used to boil water and essentially the time required to do so is accounted for natural draft and forced draft stoves. As shown in Table 4, the specific fuel consumption of TLUD stove has been always higher than that of Purti and Mpurti stoves for all studied fuels. Solid fuel burning under insufficient air (oxygen) for total combustion in the natural draft TLUD cookstove, which reduces the total amount of heat generated during the burning of the all three fuel in the TLUD cookstove. Additionally, the design of the TLUD cookstove does not reduce the heat loss from the stove materials. On the other hand, all three fuels are burnt under excess air (oxygen) to assure complete combustion in the Mpurti and Purti cookstove. The variation in specific fuel consumption for all the stoves for different fuels is shown in Table 5. The specific fuel consumption of all studied fuels tested is found to lowest for Mpurti stove and highest for TLUD stove.

3.1.4 Variation of burning rate

Burning rate (BR) is the rate at which the fuel is consumed. Equation (4) explains that the ratio of mass of the fuel consumed (f_{cd}) and time to complete the test (Δt_s). Lesser the burning rate, more time required to consume the fuel. As shown in Table 4, burning rate was found to decrease from natural draft to forced draft stove for all the fuels. The burn rate depends on providing adequate air supply. In the case of Purti and Mpurti stoves primary air is supplied through the holes present in the grate as well as from the holes at the upper end of the combustion chamber. In case of TLUD stove, the natural air was coming from the tube hole which acts as the primary air inlet, while the inner cylinder has a mesh

Table 5 Comparison of volumetric gas composition of wood pellets, coconut shell and wooden chips in TLUD, Purti and Mpurti stoves

Solid fuels	CO (%)			CO_2 (%)		
	TLUD	Purti	Mpurti	TLUD	Purti	Mpurti
Wood pellet	7.6	5.06	3.54	18.49	18.47	9.16
Coconut shell	5.5	1.68	1.14	21.1	17.90	11.46
Wood chips	9.1	3.52	2.55	22.52	18.0	12.07
Mean	7.4	3.42	2.41	20.70	18.12	10.89
Wood[a]	8			19		
Wood[b]	12–15			14–17		

[a]Varunkumar et al. (2011a, b), [b]Bocci et al. 2014)

structure at its bottom which acts as a secondary air inlet. Hence, TLUD stove has a more burning rate as compared to Purti and Mpurti stoves.

3.1.5 Variation of fire power

This is the ratio of total fuel energy consumed to boil the water divided by the total time to boil. It is the average power output of the stove during the high-power test. The performance of Mpurti stove is found to be better as compared to other stoves for all the studied fuel in cold start phase. In hot start phase and simmer phase, the performance of Purti stove is better than other stoves for all the studied fuels. Water vaporized during the water boiling test for wood pellets for all three studied stoves is given in Table 6. The results of three high-power cold start water boiling tests for TLUD, Purti and Mpurti stove are given Table 7.

3.2 Carbon monoxide and carbon dioxide concentration in exhaust gases

The experiments were carried out using three different combustion fuels by water boiling test method (WBT). The stove was loaded using fuels such as wood pellets, coconut shells and wooden chips of a known quantity. The experiments were repeated for three times to rule out any experimental errors. The fuel in the stove was ignited using kerosene soaked waste cotton. The combustible gases were collected in Tedlar bags for the combustion operation of the stove with the help of a funnel and peristaltic pump. The exhaust gases were analyzed for gaseous components CO and CO_2 using a gas chromatograph. Gas composition and gasification efficiency obtained from three different fuels are reported in Table 5. The mean value of CO and CO_2 emission for three different fuels is found to be less for the Mpurti stove as compared to Purti and TLUD stove. The wood pellets give

Table 6 Water vaporized after cold start, hot start and simmer test in all three stoves with fuel wood pellets

Phases in WBT test	Water taken initially in pot (kg)	Water vaporized in Purti (kg)	Water vaporized in Mpurti (kg)	Water vaporized in TLUD (kg)
Cold start high power (WP)	2	0.217	0.214	0.153
Hot start high power (WP)	2	0.211	0.207	0.148
Simmer test (WP)	2	0.742	0.735	0.733

Table 7 Results of three high-power cold start water boiling tests for TLUD, Purti and Mpurti stove

Performance Parameter	Mpurti			Purti			TLUD			Significant with 95% confidence
	Standard deviation			Standard deviation			Standard deviation			
	WC	WP	CS	WC	WP	CS	WC	WP	CS	
Burning rate (g/min)	0.577	1	0	0.577	0.577	0.81	0.94	0.81	1.05	Yes
Specific fuel consumption (g/l)	0.0009	0.001	0.001	0.001	0.002	0.0002	0.017	0.019	0.017	Yes
Thermal efficiency (%)	1.24	0.81	1.24	1.05	1.24	0.66	1.563	0	1.82	Yes
Fire power (W)	1.56	4.16	1.63	6.97	7.49	5.55	6.99	12.32	13.67	No
Boiling point (min)	0.81	0	1.24	0.40	1.24	1.88	1.15	1.34	1.88	Yes

fewer emissions of CO and CO_2 as compared to wood chips and coconut shells in Mpurti stove. As far as CO_2 and CO production is concerned wooden chips give less emission than other fuels in Mpurti stove. The natural draft TLUD shows major emissions in all three fuels used. The Mpurti stove also gives less emission than that reported in the literature (Varunkumar et al. 2011a, b; Bocci et al. 2014).

3.3 Indoor concentrations of $PM_{2.5}$

The experimental laboratory air concentration of $PM_{2.5}$ was detected by particulate sampler (Envirotech APM 550, Fine Particulate Sampler). As reported in Table 8, the average $PM_{2.5}$ for the natural draft TLUD stove was 1310 ± 105 μg/m^3, which was less than that of traditional cookstoves of 1383 ± 170 μg/m^3 as reported in the literature (Suresh et al. 2016). The concentration of $PM_{2.5}$ for traditional cookstoves was much higher than studied forced draft Mpurti (510 ± 45μg/m^3) and Purti stove (677 ± 40 μg/m^3). The emission concentration of improved stove is also less than low-efficient traditional cooking stoves, reported in the literature (Bailis et al. 2007; Just et al. 2013; Johnson et al. 2008; Roden et al. 2009; Venkataraman et al., 2005). Hence, concentration of PM2.5 for traditional three-stone fire stove of 1383 μg/m^3 to the improved Mpurti stove of 510 μg/m^3 represents a 63.12% reduction. An improved forced draft cookstove gives the benefit of clear and easy breath, especially to women and children.

3.4 Energy heat and structural losses due conduction, convection and radiation

Heat energy provided by fuel in all cases was calculated by multiplying the mass of fuel with calorific value, while heat taken by water was calculated by the sum of sensible heat and latent heat of water. As shown in Table 9, the actual heat loss is nothing but the difference between the actual heat provided and the heat taken by water. It is found that theoretical and actual heat loss for Mpurti stove was less than that of Purti and TLUD stove. In case of TLUD stove, the radiation losses are more due to high temperature at the outside of the wall, while heat loss from the wall at the outside for Purti and Mpurti was very negligible.

3.5 Economic analysis of stoves

A rough estimate of the total costs associated with the TLUD stove, Purti stove and Mpurti stove is given below.

Table 8 Concentration of $PM_{2.5}$ in the experimental laboratory surrounding using wood pellets, wood chips and coconut shell

Stove used	Fuel $PM_{2.5}$ (μg/m^3)			Mean (μg/m^3) (stove)	Literature (Suresh et al. 2016)
	Wood pellets	Wood chips	Coconut shell		Wood (three-stone fire stove)
TLUD	1056 (± 51)	1262 (± 146)	1614 (± 84)	1310 (± 105)	1383 ± 170 μg/m^3
Purti	616 (± 40)	764 (± 45)	652 (± 41)	677 (± 40)	
Mpurti	454 (± 65)	521 (± 28)	554 (± 46)	510 (± 45)	

Table 9 Comparison of the results for Energy heat, structural losses due conduction, convection and radiation for TLUD, Purti and Mpurti stove

Stove used	(A) Heat provided by fuel (mass of fuel × calorific value) (kJ)	(B) Heat taken by water (sensible heat + latent heat) (kJ)	Actual heat loss (A − B) (kJ)	Theoretical heat loss (conduction + convection + radiation) (kJ)
Purti	3080	2447.15	632.85	786.76
Mpurti	2833.6	2545.6	288	671.32
TLUD	4620	1981.35	2638.65	2712.85

3.5.1 TLUD stove

The cost of fabrication of a TLUD stove is Rs. 900. In this stove there is no need of external supply of electricity or any use of battery so operating cost for this stove is zero. Even though the initial cost for the TLUD is reasonably high for poor village people, but it can be reduced if it is fabricated in bulk quantity. The mass production can drop the stove cost to Rs. 300–400. The performance of TLUD stove is much better than traditional cookstove. So, the TLUD stove can be used in place of three-stone stoves. A family consumes approximately one LPG cylinder per month for their daily usage. The cost of fuel to be used in TLUD stove per month is approximately Rs. 360 which is less than half of the price of Rs. 750 for 14 kg LPG cylinder. The cost estimation of fuel includes an average household usage of the stove for at least 2 h per day. Thus, the amount of fuel required per day will be 1.5 kg of wood pellets. The market cost of wood pellets is 7–8 Rs/kg. Thus, the monthly cost of fuel would be around Rs. 360. Hence, the cost of TLUD stove (Rs. 900) can be recovered less than 3 months.

3.5.2 Purti stove

As Purti stove is available in market in bulk, the cost of fabrication was Rs. 2200. This stove battery would require 5.0 W of power to operate the fan of the forced draft cookstove. If the Purti stove average daily usage was 2–3 h then its yearly usage will became 750–1000 h. If we consider the average time required to fully charge the battery to be about 2 h. Hence, the number of charging required per year 730 h. The cost of one unit is Rs. 6–7. Therefore, total energy consumption is about Rs. 70–75. If we consider average battery life is 12 months and the cost of batteries to be Rs. 600. Hence, total operating cost per year is Rs. 675.

3.5.3 Mpurti Stove

The cost of fabrication of Mpurti stove is Rs. 2000, cost of the panel is Rs. 500, and cost of batteries is Rs. 600. As we are using solar panel operated fan, so no operating cost is required. Thus, though the initial cost of the improved modified stove is more than the Purti stove, its operating costs are much less than the latter. Hence, the Mpurti stove would prove to be more economical in the long run. The cost estimation of fuel includes an average household usage of the stove forat least 2 h per day. Thus, the amount of fuel required per day will be 1.2 kg of wood pellets. The market cost of wood pellets is 7 Rs/kg. Thus, per day cost of fuel will be Rs. 8–9. Thus, the monthly cost of fuel would be around Rs. 255 and yearly Rs. 3060 ($ 47.25). Additionally, the performance of the Mpurti stove is far better than that obtained from the Purti stove.

Thus, from the economic analysis, the recommended option for use in rural environment is the Mpurti stove. It can be a potential choice to have an efficient and clean combustion forced draft cookstoves. In addition, the heat produced can be stored in the thermoelectric generator (TEG) to generate the required power for the operation of fan as well a small amount of power to illuminate LED lights and charge mobile phones.

4 Conclusions

It is found that a forced updraft Mpurti cookstove is best suitable for wood pellets as compared to coconut shells and wood chips. Thermal efficiency and specific fuel consumption of the Purti stove remained almost constant irrespective of the fuel used. On the other hand, the specific fuel consumption of TLUD stove increases while using coconut shell as the fuel. The firepower produced by Purti stove is higher than the Mpurti stove, whereas the thermal efficiency of Purti Stove is lower than Mpurti stove, but higher than TLUD, which indicates that a large amount of the heat produced is lost in TLUD stove. It was observed that for all fuels in Mpurti stove, the parameters of boiling point, burning rate and thermal efficiency were better than those other two stoves. Thus, it was concluded that wood pellets will be the most suitable fuel for Mpurti stove. It is suggested to use wood pellets at 5–10% moisture content by sun drying them as the performance of pellets with 5–10% moisture content was shown better performance. However, wood chips and wood pellets give less volumetric compositions of CO and CO_2 as compared to coconut shell in Purti and Mpurti stoves, but reverse in TLUD stove. The indoor concentration of $PM_{2.5}$ for forced draft Mpurti stove is about 60–63% lower as compared to traditional stove. Heat balance results prove that heat loss is minimum with Mpurti as compared to other two stoves. The results obtained can play a vital role in the optimization of the performance of the gasifier stoves and can be used for further research work on gasifier stoves.

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References

Annual Book of ASTM Standard. (1983). *American society for testing of materials* (p. 19103). Philadelphia.

Arora, P., & Jain, S. (2016). A review of chronological development in cookstove assessment methods: Challenges and way forward. *Renewable and Sustainable Energy Reviews, 55,* 203–220.

Bailis, R., Berrueta, V., Chengappa, C., Dutta, K., Edwards, R., Masera, O., et al. (2007). Performance testing for monitoring improved biomass stove interventions: Experiences of the household energy and health project. *Energy Sustainable Development, 11*(2), 57–70.

Bhattacharya, S. C., Albina, D. O., & Khaing, A. M. (2002). Effects of selected parameters on performance and emission of biomass fired cookstoves. *Biomass and Bioenergy, 23,* 387.

Bocci, E. A., Sisinni, M. B., Moneti, M. C., Vecchione, L. C., Di Carlo, A. B., & Villarini, M. C. (2014). State of art of small scale biomass gasification power systems: A review of the different typologies. *Energy Procedia, 45,* 247–256.

Coffey, E. R., Muvandimwe, D., Hagar, Y., Wiedinmyer, C., Kanyomse, E., Piedrahita, R., et al. (2017). New emission factors and efficiencies from in-field measurements of traditional and improved cookstoves and their potential implications. *Environmental Science and Technology, 51,* 12508–12517.
Jetter, J., Zhao, Y., Smith, K. R., Khan, B., Yelverton, T., & DeCarlo, P. (2012). Pollutant emissions and energy efficiency under controlled conditions for household biomass cook stoves and implications for metrics useful in setting international test standards. *Environmental Science and Technology, 46,* 10827.
Johnson, M., Edwards, R., Frenk, C., & Masera, O. (2008). In-field greenhouse gas emissions from cookstoves in rural Mexican households. *Atmospheric Environment, 42,* 1206–1222.
Just, B., Rogak, S., & Kandlikar, M. (2013). Characterization of ultrafine particulate matter from traditional and improved biomass cookstoves. *Environmental Science and Technology, 47,* 3506–3512.
Li, W. (1994). Generalized equation for airflow resistance of bulk grains with variable density, moisture content and fines. *Drying Technology, 12*(3), 649–667.
Mead, D. J. (2001). The forest plantation thematic papers report plantations and wood energy (pp 5). http://www.fao.org/tempref/docrep/fao/006/ac125e/ac125e00.pdf.
Mukhopadhyay, R., Sambandam, S., Pillarisetti, A., Jack, D., Mukhopadhyay, K., & Balakrishnan, K. (2012). Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: An exploratory study to inform large scale interventions. *Global Health Action, 5,* 19016.
Mukunda, H. S., Dasappa, S., Paul, P. J., Rajan, N. K. S., Yagnaraman, M., & Ravikumar, D. (2010). Gasifier stoves science, technology and field outreach. *Current Science, 98,* 627.
Prasad, K. K., Sangen, E., & Visser, P. (1985). Wood burning cookstoves. *Advanced Heat Transfer, 17,* 159–317.
Reed, T. B., & Larson, R. A. (1996). Wood gas stove for developing countries. In: A. V. Bridgwater (Ed.) *Developments in thermo-chemical biomass conversion conference Banff, Canada* (pp. 20–24). Blackie Academic Press.
Roden, A., Bond, T., Conway, S., Osorto Pinel, A., MacCarty, N., & Still, D. (2009). Laboratory and field investigations of particulate and carbon monoxide emissions from traditional and improved cookstoves. *Atmospheric Environment, 43,* 1170–1181.
Stahl, M., Granstrom, K., Berghel, J., & Renstrom, R. (2004). Process for biomass drying and their effects on the quality properties of wood pellets. *Biomass and Bioenergy, 27,* 621–628.
Still, D., MacCarty, N., Ogle, D., Bond, T., & Bryden, M. (2011). *Test results of cookstove performance*. Cottage Grove, OR: Aprovecho Research Center; London: Shell Foundation; Washington DC: U.S. Environmental Protection Agency.
Suresh, R., Singh, V. K., Malik, J. K., Datta, A., & Pal, R. C. (2016). Evaluation of the performance of improved biomass cooking stoves with different solid biomass fuel types. *Biomass and Bioenergy, 95,* 27–34.
Tryner, J., Marchese, A. J., & Willson, B. D. (2013). The effects of fuel type and geometry on emissions and efficiency of natural draft semi-gasifier biomass cookstoves. In *8th U. S. National Combustion Meeting, the University of Utah* (pp 3–4).
Varunkumar, S., Rajan, N. K. S., & Mukunda, H. S. (2011a). Single particle and packed bed combustion in modern gasifier stoves—density effects. *Combustion Science and Technology, 183*(11), 1147–1163.
Varunkumar, S., Rajan, N. K. S., & Mukunda, H. S. (2011b). Experimental and computational studies on a gasifier based stove. *Energy Conversion and Management, 53,* 135.
Venkataraman, C., Habib, G., Eiguren-Fernandez, A., Miguel, A., & Friedlander, S. (2005). Residential biofuels in south Asia: carbonaceous aerosol emissions and climate impacts. *Science, 307,* 1454–1456.
Wendelbo, P. (2012). The Peko Pe biomass household energy program. Available at: http://wendelborecho.wordpress.com/2012/05/10/downloads. Accessed November 29, 2012.
Witt, M. J. (2005). An improved wood cookstove: Harnessing fan driven forced draft for cleaner combustion. Hartford CT: Trinity College; Cottage Grove, OR: Aprovecho Research Center.