Thermal Performance Evaluation of an Improved Biomass Cookstove for Domestic Applications

Raktimjyoti Barpatragohain, Niyarjyoti Bharali, and Partha Pratim Dutta

Abstract Biomass fuels are normally burnt inefficiently using the traditional cookstoves in rural areas. The uncontrolled harmful emissions released due to the combustion of biomass cause various respiratory problems to the users. Thus in order to overcome such problems related to the traditional cookstove, an improved biomass cookstove is proposed in the present study. An effort is made to design and fabricate an improved biomass cookstove to study various heat losses from it and performance parameters. Water boiling test (WBT) was conducted for understanding the overall performance of the improved stove. Results of WBT were compared with a commercially available biomass cookstove. The average thermal efficiency while boiling 7.5 L water was ~33%, whereas the average thermal efficiency in case of the commercial stove was ~23%. While boiling 7.5 L water in this improved stove, the performance was better than the commercial stove with respect to specific fuel consumption. The maximum level of CO was detected around 20 ppm during the start and it reduced to 5 ppm as combustion progressed. Both the values for CO_2/CO and indoor air quality were within acceptable limit.

Keywords Improved cookstove · Biomass combustion · Thermal performance · Water boiling test · Emission

Nomenclature

w_v	Mass of water vaporized (g)
$P1_i$	Mass of pot of water before test (g)
$P1_f$	Mass of pot of water after test (g)
Δt_c	Time to boil (min)
t_i	Time at start of test (min)

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t_f	Time at end of test (min)
Δt_c^T	Temperature-corrected time to boil (min)
$T1_i$	Water temperature at start of test (°C)
$T1_f$	Water temperature at end of test (°C)
TE	Thermal efficiency (%)
w_{cv}	Water vaporized (g)
r_b	Burning rate (g/min)
f_c	Mass of biomass combusted (g)
f_{cd}	Energy released (kJ)
h	Heat transfer coefficient (W/m^2 K)
SC_c	Specific fuel consumption (kJ/g)
Re	Reynold number
Pr	Prandtl number

1 Introduction

Biomass is a suitable renewable energy source that would help to overcome fossil fuel dependency partially. Combustion of biomass releases carbon dioxide in the atmosphere but biomass is considered as a carbon-neutral source because it raptures the same amount of carbon dioxide while growing [1]. Biomass energy sources are various domestic wastes, wood, rice husk, etc. These types of various biomass fuels are widely used in industrial furnaces as well as in domestic cooking stoves to produce heat [2]. Bryden and Maccarty [3] observed that biomass fuels deviated in numerous ways from the conventional fossil fuels used in combustion processes, such as coal. They usually have high moisture contents, lower heating values, and a range of trace constituents, such as chlorine, sulfur, phosphorus, nitrogen, and a variety of ash-forming metals. These special properties of biomass fuels pose some challenges; but in many cases it provides advantages to their use in combustion methods. Design of the combustion devices and choice of their operating constraints are very much dependent on the thermophysical properties of the biomass fuels. Fichet et al. [4] reported that biomass had established itself as an energy carrier accomplished with the growing demand of clean and sustainable energy.

2 Literature Review

CFD analysis is an effective approach for evaluating the performance of a biomass furnace complementing conventional combustion analysis in a laboratory. It enables the researchers to study the different combustion reactions involved inside the furnace. By optimizing combustion air (fluid) flow, CFD analysis shows a path to improve the overall efficiency [5–7].

Similarly, water boiling test (WBT) is a very effective methodology for evaluating the biomass stove performance. WBT gives a fair assessment based on the effectiveness and efficiency of different designs. With the help of WBT, the rate of emissions can also be estimated [8–10]. Water boiling test has been applied comprehensively in studying and exploring the combustion characteristics of firewood and recent fuels in traditional and improved biomass cookstoves. Thermogravimetric analysis is used to study the thermal behavior of solid fuels vis-a-vis the ignition behavior of coal, biomass, and coal-biomass blends. Using TGA, one can distinguish the impact of particle size and shape on the thermal behavior of biomass [11–14].

Bhuiyan et al. [1] had executed a 3D numerical modeling of biomass pallet combustion under diverse combustion environments. The effects of overall flame temperatures, species concentration, solid-phase variables, and ignition front spread velocity were reported. Gogoi and Baruah [2] developed a steady-state heat transfer model to forecast the performance of a biomass stove with varying operating and design environments like composition, particle shape and size, shape and material of the combustion chamber. Bryden and Maccarty [3] reviewed the cookstove modeling process for one to three burners, natural draft, wood-fired cookstoves fueled with untreated biomass of different sizes. Fichet et al. [4] had developed a CFD-based model for wood combustion in the domestic stoves with a special emphasis on CO and CO_2 emissions. The CFD-based model was constructed in the framework of RANS approach. They suggested measures for the reduction of emissions and enhancing in overall efficiency. Still et al. [5] did some laboratory experiments regarding the filtration and retained heat for reduction of particulate matter (PM) emissions from biomass cooking. They used WBT test in a closed enclosure. They found that the rates of PM emission were significantly reduced from 7.5 mg/min of PM to 1.5 mg/min of PM.

Quist et al. [7] studied the performance for a basic brick channel cookstove with uncertainty analysis. Grimsby et al. [8] used different biomass fuels like maize stalks, stalks from sunflower in the improved cookstoves and assessed them with (WBT). Djurovic et al. [9] showed that the efficiency of the biomass furnace could be increased and the amount of CO emission could be reduced by proper furnace dimensioning. It also helped in reducing the cost of the furnace. Chen et al. [10] studied the performance of pellet-gasifier stoves, efficiency, and pollutant emissions with the help of WBT. They compared with traditional stoves and different biomass fuels along with the quantity of particulate matter (PM) emitted.

Performance of different types of improved solid biomass cookstoves and the thermal efficiencies were reported in the literature [12]. Shiehnejadhesar et al. [13] had studied about the virtual biomass grate furnace that was comprised of a comprehensive CFD model of all relevant processes for simulation. Lung and Espira [14] presented wood consumption data using kitchen performance tests over an area 3000 km^2 for 7 years on a modified traditional cookstove named *Upesi* ceramic stove. This improved cookstove was meant for communities around a threatened rainforest in western Kenya. They found using the *Upesi* improved cookstove significantly reduced daily wood consumption by 3.87 kg per household, a mean saving of 37.7%. Lombardi et al. [15] performed an investigation on techno-economics prospective of a fully renewable solar micro-grid, ensuring an integrated access to electricity and clean cooking, based on two representative case studies in Tanzania, namely (i) a residential case study and (ii) a community service case study. An inexpensive potassium-based catalyst was incorporated in a chimneyless biomass cookstove reducing harmful emissions through catalytic oxidation [16]. Fine particulate matter and black carbon concentration levels were monitored uninterruptedly inside two types of kitchens that were separated from and attached to the main house under actual cooking practices [17]. Dutta et al. [18–20] studied biomass gasifier improved burners for balck tea drying. Sharma and Jain [21] investigated the impact of increased levels of indoor air pollution caused due to biomass combustion in the rural household of northern India. Gohain and Dutta [22] studied on thermal modeling of an improved biomass cookstove for the rural area. Based on the above literature, the objective of the present work is design and thermal performance testing of an improved biomass cookstove for rural applications.

3 Material and Methodology

3.1 Mathematical Modeling

The important mathematical relationships those are used during the performance testing with the help of water boiling test are as follows [23, 24]:

1. Mass of water vaporized is calculated as:

$$w_\mathrm{v} = P1_\mathrm{i} - P1_\mathrm{f} \tag{1}$$

2. Time to boil the pot:

$$\Delta t_\mathrm{c} = t_\mathrm{f} - t_\mathrm{i} \tag{2}$$

3. The temperature-corrected time to boil is calculated by the following equation:

$$\Delta t_\mathrm{c}^\mathrm{T} = \Delta t_\mathrm{c} \frac{75}{T1_\mathrm{f} - T1_\mathrm{i}} \tag{3}$$

4. The thermal efficiency is an estimate of the total energy produced by the fire that is used to heat the water in the pot. It can be calculated by the following mathematical relationship:

$$\mathrm{TE} = \frac{\Delta E_{\mathrm{H_2O}} + \Delta E_{\mathrm{H_2O,evap}}}{E_\mathrm{released}} \tag{4}$$

where

$$\Delta E_{H_2O} = m_{H_2O}\left(C_p(T_b - T_{fuel}) + \Delta h_{H_2O}\right) \tag{5}$$

$$\Delta h_{H_2O} \approx 2257\,(\text{kJ/kg}) \tag{6}$$

$$T_{fuel} = T_a \tag{7}$$

$$E_{released} = f_c \cdot \text{LHV};\ \Delta E_{H_2O,evap} = w_{cv} \times 2260\,(\text{kJ/kg})$$

5. The burning rate can be calculated by the following expression:

$$r_b = \frac{f_c}{\Delta t_c} \tag{8}$$

6. The specific fuel consumption is calculated by the following expression:

$$\text{SC}_c = \frac{f_{cd}}{f_c} \tag{9}$$

Equations for calculating air velocity and heat loss:

The theoretical velocity of the gas inside the combustion chamber was estimated by the following mathematical relationships [25, 26]:

$$v_{th} = \sqrt{2 \times g \times H \times \left(\frac{T_g}{T_a} - 1\right)} \tag{10}$$

From the continuity equation, the theoretical mass flow rate of the flue gases can be calculated [25, 26]:

$$\dot{m}_{th} = \frac{353}{T_g} \times A \times \sqrt{2 \times g \times h \times \left(\frac{T_g}{T_a} - 1\right)} \tag{11}$$

Heat loss to the surrounding can be calculated by the following expression:

$$Q_{heatloss} = \frac{\left(T_g - T_a\right)}{\frac{1}{(h_{ci}+h_{rfl}+h_{rch})} + \frac{\ln\left(\frac{D_o}{D_i}\right)}{2\times\pi\times H\times k_i} + \frac{1}{(h_{co}+h_{ro})A_o}} \times \frac{1}{1000 \times m_f} \tag{12}$$

where, for the fully developed turbulent flow, the following expression can be used [25, 26]

$$h_{\mathrm{ci}} = \frac{k}{D} \times 0.023 \times \mathrm{Re}_D^{0.8} \times \mathrm{Pr}^{0.3} \tag{13}$$

From average Nusselt number expression for natural convection, we get the following expression [25, 26]

$$h_{\mathrm{co}} = \frac{k}{H} \times 0.59 \times \left(\mathrm{Ra}_H^{0.25}\right) \tag{14}$$

$$h_{\mathrm{rfl}} = \frac{\sigma \times \left(\varepsilon_{\mathrm{g}} T_{\mathrm{g}}^4 - \alpha_{\mathrm{g}} T_{\mathrm{wi}}^4\right)}{\left(T_{\mathrm{g}} - T_{\mathrm{wi}}\right)} \tag{15}$$

$$h_{\mathrm{ro}} = \sigma \times \varepsilon_{\mathrm{o}} \times \left(T_{\mathrm{wo}}^2 + T_{\mathrm{a}}^2\right) \times \left(T_{\mathrm{wo}} + T_{\mathrm{a}}\right) \tag{16}$$

$$h_{\mathrm{rch}} = \frac{\sigma \times \left(T_{\mathrm{char}}^2 + T_{\mathrm{wi}}^2\right) \times \left(T_{\mathrm{char}} + T_{\mathrm{wi}}\right)}{\frac{(1-\varepsilon_{\mathrm{c}})}{\varepsilon_{\mathrm{c}}} + \frac{F_{\mathrm{char-wall}} + F_{\mathrm{char-pot}}}{F_{\mathrm{char-wall}} \times \left(F_{\mathrm{char-wall}} + 2 \times F_{\mathrm{char-pot}}\right)}} \tag{17}$$

4 Experimental Procedure

Two different pots with carrying capacity 5 and 7.5 L were used during the tests. These are the two standard weights taken during the WBT test protocol. The test started with initially taking the weight of water needed for boiling, i.e., whether 5 or 7.5 L. The initial weight of the biomass used for combustion was noted. A calibrated thermocouple was placed in the pot containing water for determining the temperature rise at a regular time interval. A stopwatch was kept ready as soon as the test started for recording the time required for boiling water in every phase.

WBT consists of three phases, i.e., cold start, hot start, and simmering. With the ignition of the biomass as the combustion process starts, the first phase of the test, i.e., cold start, begins. This phase remains till the first water bubble touches the water surface. Another thing noted throughout the test was that, even though water boils at 99/100 °C, this result holds true if the water is boiled at the sea level. However, during the test it was observed that water started boiling at different temperatures varying from 96 to 99 °C. Some of the reasons of this variation may be due to the pressure difference and the impurities present in the water causing the difference of the boiling point. As soon as the water reached the boiling point temperature, the process was stopped. After that, the final weight of the pot with water and the fuel with the container was measured. The amount of time consumed during the first phase was recorded, and the amount of charcoal produced during the first phase was measured. After collecting all the essential data, immediately the pot was emptied and freshly filled it with the same amount of water initially taken during the cold phase. The only difference in this phase is that water is being collected and weighted

Table 1 Technical specifications of instrument used for the water boiling test

S. No.	Name of the instrument	Make/model	Variable ranges	Accuracy/resolution
1	K type thermocouple and digital thermometer	MLABS/HT-9815	−200 to 1372 °C	±1 °C
2	Anemometer	AMV06	0–20 m/s	±1%/0.1 m/s
3	Infrared thermometer	HTC/HTC/MT-4	−50 to 550 °C	±2/0.1 °C
4	Weighing machine	Bijnath	0–10 kg	0.1 g
5	Moisture meter	MD 3G	5–40%	±1%
6	Bomb calorimeter	Saiyam/MD4G	Changsha	
7	CO_2/CO analyzer	5E-1AC/ML TESTO-435	0–10,000/0–500 ppm	±5 ppm/±1 ppm

when the pot is still hot. Hence, the second is called as the hot start. The process is repeated similar to the cold start, and all the necessary data were collected. The third phase or final phase is called simmering. In this phase as soon as the hot start is completed, the pot is kept under observation for 45 min. During this period, the tester has to maintain the temperature between 96 and 99 °C. This step simulates the long cooking of legumes or pulses common throughout the world [8].

5 Experimental Setup

The following instruments were used for performance evaluation of improved biomass stove for domestic application (Table 1).

6 Results and Discussion

The experimental setup of an improved biomass stove which is used for water boiling test has been presented in the Fig. 1a, b. A double-walled cookstove was fabricated, where the inner combustion chamber was made up of stainless steel while the outer cylinder was made up of mild steel. The results of water boiling test of the designed biomass stove are compared with a commercial greenwood cookstove, and they are presented in Table 2.

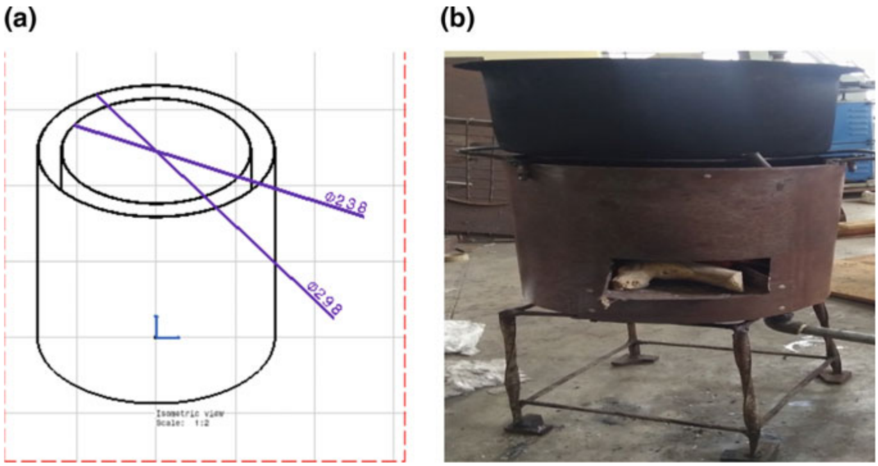

Fig. 1 **a** Double-walled biomass furnace. **b** Biomass furnace water boiling test

Table 2 Performance comparison of designed cookstove with greenwood commercial cookstove

Greenwood commercial stove		Improved biomass cookstove	
Performance parameters		5 L test	7.5 L test
Net change in char (g)	79	56	70
Time to boil (min)	26	16	18
Temperature-corrected time to boil (min)	24	15	16
Burning rate (g/min)	15.53	16	18
Specific fuel consumption (g/L boiled)	86	115	80
Overall thermal efficiency (%)	22	26	31

Table 2 shows comparative results of the important performance parameters of both the commercially available stove and the improved biomass cookstove. Tests were conducted on both the stoves under similar experimental conditions. It is evident from Table 2 that the results in case of the designed and fabricated model were better than the commercial stove. The average time for boiling in case of present model was better than the commercial stove. Other parameters like the specific fuel consumption, net amount of char produced due to the burning of biomass were less in comparison to the commercial stove. As a result, it enhanced the overall thermal efficiency of the improved stove. Thus, the overall efficiency of present model tested with two different weights was found better than the greenwood commercial stove.

Figure 2a represents a fair comparison of thermal efficiencies with water boiling point temperatures. Water boiling test (WBT) was conducted on the designed and fabricated cookstove with two different water weights, and the results were

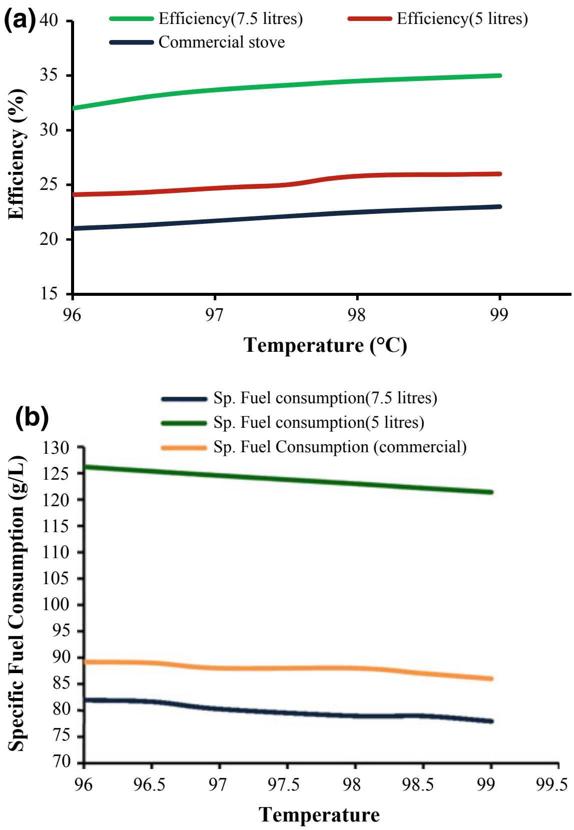

Fig. 2 **a** Variation thermal efficiency with boiling temperature of water. **b** Variation of specific fuel consumption with boiling temperature of water

compared with a commercial cookstove under similar experimental conditions. It can be seen from the plot that the thermal efficiencies of the fabricated cookstove under both the cases, i.e., 5 and 7.5 L, were better than the commercial greenwood cookstove. The average thermal efficiency in case of 7.5 L was around 33%, and in case of 5 L test, it was around 25%, whereas the average thermal efficiency in case of the commercial stove was 23% respectively.

Figure 2b represents the variation of specific fuel consumptions with water boiling point temperatures. WBTs were conducted on both the fabricated model and the commercial cookstove. The lower the specific fuel consumption, the better is the performance of the cookstove. Results showed that in case of 7.5 L when tested in the present designed model, specific fuel consumption (average 80 g/L) was better than the commercial stove, whereas in case of 5 L test, the specific fuel consumption was more comparing to the commercial stove. The reason for such result is because of the spread of flame from the sides of the pot and the full capacity of the stove was not utilized. This resulted in the loss of heat that led for an increment of the fuel consumption in order to provide sufficient heat to the pot's bottom.

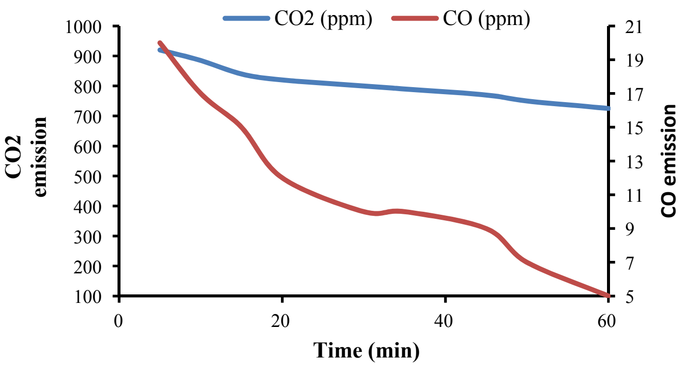

Fig. 3 In door variation of carbon dioxide and carbon monooxide with time during water boiling test

Figure 3 represents the characteristic plots of CO_2 and CO emission (near the cookstove) with time for the improved designed cookstove. CO_2 and CO are very important emission factors that should be kept under consideration while designing a biomass cookstove. As per standard, the values of CO_2 and CO should not increase above 1000 ppm in case of CO_2 and 25 ppm in case of CO when used for domestic cooking purpose. Gas analyzer was used to detect the emission levels while the test was performed. The maximum level of CO_2 detected was 920 ppm which was during the start of combustion. As the combustion process progressed, the CO_2 emission gradually reduced to 820 ppm. So was in the case of CO, which was detected around 20 ppm during the start and reduces to 5 ppm as the combustion progressed. .

The thermal performance results of present improved biomass cookstove are validated with Bhuiyan et al. [1], the normal combustion rate of biomass in an improved cookstove. Gogoi and Baruah [2] observed thermal efficiency 23.63% and time of boiling 16.94 min. The present results with improved biomass cookstove boiling 5 L water 16 min with an average 24.50% thermal efficiency. Therefore, this cookstove may be recommended for domestic applications in rural areas.

7 Conclusions

Thermal performance evaluation of an improved biomass cookstove is demonstrated with water boiling test performed in the laboratory condition. Its performance was compared with a commercially available greenwood cookstove. The average thermal efficiency for boiling of 7.5 L water was around 33% and in case of 5 L water boiling, it was found around 25%. The average thermal efficiency in case of the commercial stove was found 23%. The maximum level of CO_2 detected was 920 ppm which was during the start of combustion. As the combustion process progressed, the CO_2 emission gradually stabilized at 820 ppm. CO was detected around 20 ppm during the start and stablized at 5 ppm as combustion progressed This is well within the tolerable limit of healthy human being.

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