RESEARCH ARTICLE

Effect of Height, Shape and Air Supply in the Performance of Wood Burning Cookstoves

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ABSTRACT

More than half the kitchens in the world use traditional wood burning stoves for cooking. The traditional stove involves burning of wood in open which leads to inefficient combustion with 5 to 10 % thermal efficiency. In this study, highly improved stoves were designed and developed by varying height, shape and air supply. It was observed that the cylinder shaped stoves performed with higher thermal efficiency than the frustum stoves. The height of the combustion chamber was optimized at 12 cm with better combustion (19.83%) and higher heat transfer rate (20.15%). The primary air supply of 80 % and secondary air of 20 % resulted in higher combustion temperature (660.9 °C) and lesser air pollutants of 0.82 g L^{-1} (CO) and 142 g L^{-1} (HC). The cylindrical combustion chamber of height 12 cm with primary sir supply and secondary air supply of 80 and 20 %, respectively resulted to higher thermal efficiency of 22.86 %, specific fuel consumption of 0.59 kg L^{-1} and heat transfer efficiency of 23.08 %.

Keywords: *Mud stove, combustion chamber, thermal efficiency, specific fuel consumption*

Modification of shapes and sizes in the pots headed in the shielded-fire development from open fires to three stone arrangement and then to U-shape mud cookstoves called traditional cookstoves (Kumar *et al*., 2013). These traditional stoves have problems of lower energy conversion (5 to 10 %), smoke nuisance, lower useful power output (0.5 to 0.8 kW), health hazards and necessitating a periodic blowing, longer time for cooking, tending of fire etc. (Jayaraman *et al*., 1989).

Indoor air pollution from cooking or heating of biomass fuels affects the health of about 2000 million people in the world. In developing countries, 730 million tonnes of biomass are burned every year causing 1000 million tonnes of carbon dioxide emission into atmosphere (Raman *et al*., 2013). Every year 1.5 million people died and several others affected with different diseases because of smoke from open fires and traditional cookstoves (Kumar *et al*., 2013). Over many years, awareness on environmental and social costs of wood stoves usage has grown significantly.

Operation at stoichiometric air conditions with excess air leads to higher combustion temperature resulted in better heat transfer and higher cookstoves efficiency. The air inflow into the combustion chamber in the form of primary and secondary air sustains the combustion process. Providing the secondary air supply in the chamber design resulted in limiting heat losses to the surroundings (Sutar *et al*., 2015). The life span of chimney attached cookstoves were much lower due to the utilization of clay and sand. More durable materials such as ceramic and metals were utilized to increase the life span of cookstoves in early 2000's. Even though with these improvements thermal efficiency of stoves was still lower due to incomplete combustion where the stoves could not be operated at near stoichiometric conditions (Raman *et al*., 2013).

This study has been carried out with a specific objective to determine the optimum shape and height of stove for improving the performance of cookstove and optimum primary and secondary air flow combination in the stove for complete combustion.

MATERIAL AND METHODS

In this section, techniques for fuel wood characterization, descriptions of stoves developed and performance evaluation of these stoves are mentioned.

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Fuel wood characterization

The Casuarina equisetifolia has been chosen as fuel wood for the study because of its availability and is one of the prominent fuel woods used for domestic thermal applications. The proximate analysis using standard ASTM procedures (moisture content - ASTM D--3173, volatile matter - ASTM D-3175 and ash content - ASTM D-3174) and ultimate analysis were performed using the elemental analyser (thermo scientific, Flash 2000). The calorific value of Casuarina equisetifolia was determined using bomb calorimeter (ASTM D-2015-77). The thermo-gravimetric analysis was conducted using thermo gravimetric analyser (Q50, TA instruments) to find the combustion characteristics (weight loss for increase in temperature per time) of the selected fuel wood.

Experimental details

The stoves were made of mud mixtures such as clay, sand and paddy straw dust (1:1:1). For optimizing the height of the stoves, combustion volume (0.003825 m^3) and diameter (20 cm) of the stove were calculated based on stoichiometric air supply to fuel. The shape has been varied as cylinder and frustum. The primary and secondary air supply for improving the combustion in the combustion chamber was calculated for four different ratios (60 % - 40 %, 70 % - 30 %, 80 % - 20 % and 90 % - 10 %). The number of holes varied for supplying the primary and secondary air combinations are shown in table 1. The description of stoves are mentioned in table 2.

Performance evaluation of stoves

The performance of improved stoves was evaluated with parameters such as time to boil, specific fuel consumption, thermal efficiency and heat transfer efficiency. The developed stoves were tested by using water boiling test protocol 4.2.3 (USEPA, 2014). The emission from the hood system was estimated using exhaust gas analyser (Model KM9106).

RESULTS AND DISCUSSION

In this section, the characterization of fuel wood and results of performance evaluation of different cookstoves are discussed.

Table 1. Characteristics of Casuarina equisetifolia

Parameters	Value
Proximate analysis	
Volatile matter (%)	77.25
Ash content (%)	0.56
Fixed carbon (%)	22.19
Ultimate analysis	
Carbon (%)	45.52
Hydrogen (%)	6.95
Oxygen (%)	46.39
Nitrogen (%)	0.50
Sulphur (%)	0.44
Higher Calorific Value (MJ kg^{-1})	21.76

Fuel wood characteristics

The proximate analysis, ultimate analysis and calorific value of fuel wood were determined as per the procedure described in ASTM standards. The moisture content of wood was 5.6 % which is in the preferable range for good combustion. The selected wood had 77.25 % volatile matter and ash content of 0.56 %. Low ash content biomass was considered as better feedstock for combustion. Fixed carbon content of 22.19 % was observed in the selected fuel wood species. More the fixed carbon, more the energy input during combustion by the wood (Senelwa and Sims, 1999). The selected wood had 45.52 % of carbon, 0.5 % of nitrogen and 0.44 % of sulphur, 6.95 % of hydrogen and oxygen of 46.39 %. In thermo-gravimetric analysis, the first stage from 40 to 200 °C was characterized by a lesser weight loss (5.94 %) which was due to evaporation of moisture. The major weight loss was observed in the range of 200 to 400 °C and was due to the thermal degradation of volatile matter of about 62.5 %. During the combustion of fuel, volatile matters escaped after moisture and burned in the gaseous state leaving the fixed carbon as char. Increase in temperature from 400 to 800°C resulted in a weight loss of 12.42 % showed that the carbonaceous matters in wood continuously decomposed at slower rate. The weight loss in wood based on the temperature rise in time is shown in Fig 1.

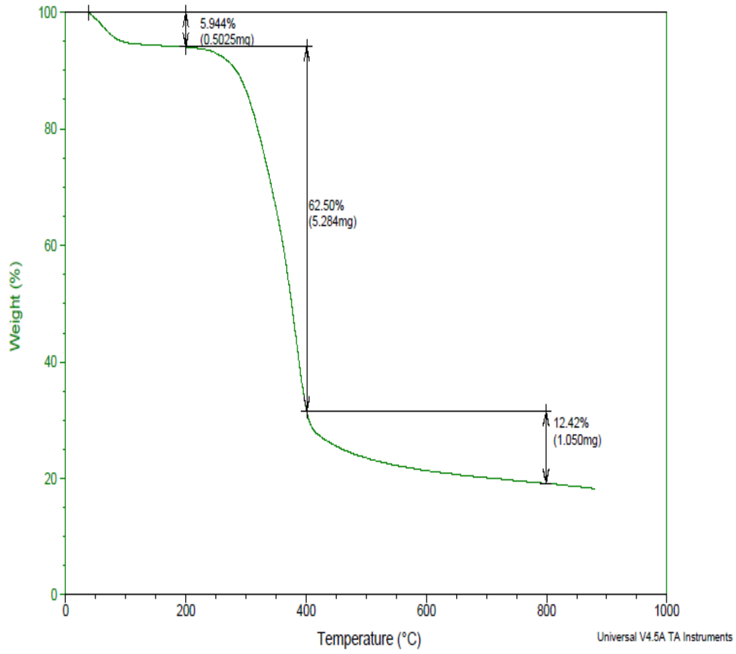

Figure 1. Thermo gravimetric analysis of *Casuarina equisetifolia*

Performance evaluation of stoves

The performance of the stoves such as thermal efficiency, specific fuel consumption, heat transfer efficiency and power output were evaluated for fuel feed rate of 1 kg h^{-1}.

Table 2. Combination of primary and secondary air supply

Primary air supply		Secondary air supply	
Combination (%)	No. of holes	Combination (%)	No. of holes
60	6	40	30
70	14	30	22
80	21	20	15
90	28	10	8

Specific fuel consumption, heat transfer efficiency and power output

From the table 4, it is observed that increased efficiency resulted in higher power output rating of stoves. The specific fuel consumption was reduced by improving the stove parameters. The heat transfer efficiency of S2 stove was 2.27 % higher than the S1 stoves. Reduced height of stove increases the heat transmission efficiency to the vessel (Bhatt, 1984). The height of 12 cm stove resulted higher heat transfer efficiency of 1.48 % than 14 cm height stove. Due to presence of constant cross sectional area, cylinder stove showed improved heat transfer and reduced heat loss to wall than the frustum stove. Cylinder shaped stove (S2) resulted higher heat transfer efficiency of 1.07 % and lower specific fuel consumption of 0.07 kg L^{-1} than frustum shaped stove (S4). By improving the primary and secondary air supply, S7 stove resulted least specific fuel consumption of 0.59 kg L^{-1}. Air supply in combustion chamber resulted in reduced fuel usage by 0.1 kg, improved heat transfer efficiency by 2.93 % and increased power output rating by 0.18 kW. The primary air (80 %) and secondary air (20 %) supply in 12 cm cylinder stove showed the highest heat transfer efficiency and lower specific fuel consumption. It is evident that 80 % primary air supply provided better fuel combustion and 20 % secondary air supply provided better combustion of released volatiles. Hence, this combination of primary and secondary air supply has been selected for further insulation studies in cookstoves. The frustum shaped stoves showed the reduced fuel usage by 0.07 kg, heat transfer efficiency improved by 1.95 % and power output increased by 0.09 kW than S4 stove.

Table 3. Description of stoves

Parameters	Type
Shape - Cylinder	
Height 10 cm	S1
Height 12 cm	S2
Height 14 cm	S3
Primary -60% Secondary -40%	S5
Primary -70% Secondary -30%	S6
Primary -80% Secondary -20%	S7
Primary -90% Secondary -10%	S8
Shape - Frustum	
Height 12 cm	S4
Primary -60% Secondary -40%	S9
Primary -70% Secondary -30%	S10
Primary -80% Secondary -20%	S11
Primary -90% Secondary -10%	S12

Thermal efficiency

The thermal efficiency of height and shape varied stoves were tested and results were mentioned in the table 4. For 12 cm height stove (S2) resulted higher thermal efficiency of 19.83 %. Increasing the height to 14 cm, results to a thermal efficiency of 1.49 % less than the S2 stove due to reduced heat transfer rate. The frustum shape (S4) stove, resulted 1.07 % lower thermal efficiency than the cylinder stove due to higher heat loss in the top of the stove. By supplying separate primary and secondary air in the combustion chamber, the thermal efficiency was increased by 3.03 %. The required amount of secondary air supply increased the combustion temperature of stove (Kirch *et al.*, 2016). The thermal efficiency increased by increasing the primary air supply and reduced at 90 percent due to the inadequate supply of secondary air for combustion of gaseous mixture released from the fuel. S7 stove showed the thermal efficiency of 3.6 % higher than the S2 stove. The primary and secondary air supply in the cylinder stove showed the increased thermal efficiency of 2.42 % than frustum shaped stove. Improper combustion was occurred by decreasing the secondary air supply from 20 % to 10 % resulted the reduced thermal efficiency by 1.32 %. Higher thermal efficiency of 22.86 % was achieved for cylinder stoves with height 12 cm and air supply in combinations of primary (80 %) and secondary (20 %).

Table 4. Performance evaluation of stoves for fuel feed rate 1 kg h^{-1}.

Stove type	Specific fuel consumption (kg L^{-1})	Heat transfer efficiency (%)	Power output rating (kW)	Thermal efficiency (%)
Shape – cylinder				
S1	0.83	17.94	1.07	17.62
S2	0.69	20.15	1.20	19.83
S3	0.79	18.67	1.11	18.34
S5	0.75	19.43	1.16	19.23
S6	0.67	20.78	1.24	20.55
S7	0.59	23.08	1.38	22.86
S8	0.64	21.74	1.30	21.54
Shape – frustum				
S4	0.76	19.08	1.13	18.76
S9	0.77	18.85	1.13	18.66
S10	0.75	19.41	1.16	19.23
S11	0.69	20.67	1.23	20.42
S12	0.72	19.90	1.18	19.56

Effect of height in emission reduction

From the table 5, it is observed that S1 stove emitted higher amount of CO and HC than S2 and S3 which denotes the incomplete combustion. The HC emission was more during incomplete combustion of wood (Barrefors and Petersson, 1995). The emission from S3 stove was lesser compared with S1 and S2 stoves. Frustum shape led to higher air velocity which reduced the emission of CO (Okafor and Unachukwu, 2012). The frustum shaped S4 stove released 0.3 g L^{-1} of lesser CO emission than cylinder shaped stove. The higher emission of CO resulted in lower combustion temperature and higher CO_2 emission resulted in higher combustion temperature in the combustion chamber (Vicente *et al.*, 2015).

Table 5. CO, CO_2 and HCs emission from the stoves

Stove	CO (g L^{-1})	CO_2 (g L^{-1})	HC (g L^{-1})
S1	2.90	7.6	435
S2	2.20	10.3	333
S3	2.50	9.1	376
S4	2.60	9.3	390
S5	1.60	12.5	280
S6	1.20	14.8	217
S7	0.82	19.1	142
S8	0.90	17.2	186
S9	1.50	11.6	310
S10	1.35	13.6	225
S11	1.00	16.8	165
S12	1.05	15.4	173

Effect of primary and secondary air supply

The primary and secondary air supply in the combustion chamber reduced emission of stove (Ko and Lin, 2003). The emission studies resulted that lesser CO (0.82 g L^{-1}) and HC (142 g L^{-1}) for the stove S7 as this stove provided better combustion environment with optimized primary and secondary air supply, stove dimensions and shape. By providing the primary and secondary air in cylinder stove, the emission of CO was reduced by 1 g L^{-1}. Increasing the primary air supply, the reduction of CO (1.78 g L^{-1}) and HC (204 g L^{-1}) emissions was found. This indicates the higher combustion temperature and complete combustion of fuel in the cookstoves.

CONCLUSION

In this study on the cookstove by varying the height as 10, 12 and 14 cm, shape as cylinder and frustum and air supply of primary as 60, 70, 80 and 90 % and secondary as 40, 30, 20 and 10 % revealed the difference in performance of stove for varying the parameters. It is concluded that the primary air supply of 80 % and secondary air supply of 20 % resulted in increased thermal efficiency of 3.02 % than the 12 cm height stove without secondary air supply. The cylinder stoves resulted in 1.53 % higher efficiency than the frustum stoves at this air supply combination also. For the fuel feed rate of 1 kg h^{-1}, S7 (12 cm cylinder stove with 80% primary and 20% secondary air) stove obtained higher thermal efficiency of 22.86 % than other stoves S5, S6, S8, S9, S10, S11 and S12. The reduced fuel usage by 0.16 kg, improved heat transfer efficiency by 3.65 % and increased power output rating of 0.16 kW in S7 stove were observed. The CO emission from the S7 stove was lower than the other stoves.

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