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Experimental Study on the Performance of an Indigenous Wood Stove for Indian Rural Cooking

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Abstract- An indigenous wood stove is designed and fabricated with a goal of lowering fuel consumption, decreasing soot emission and increasing thermal efficiency. Available rural wood stoves produce thermal efficiency in the range of 9% - 11% using Indian wood, and they produce significant carbon deposit on the vessels. Present stove is made of 2 mm thick mild steel sheet shaped as concentric square cylinders with a grate plate at the bottom. The side length of inner and outer square cylinders are 130 mm and 180 mm, respectively and their height is 270 mm. The stove is supported by a stand, such that grate is at 55 mm from the ground. Holes are drilled on the surfaces of both walls to facilitate proper air entrainment. Casuarina wood, commonly used in rural areas of India, is chopped into small cylindrical pieces with diameters ranging from 32 mm to 34 mm and length 125 mm. The calorific value of the wood is 17 MJ/kg. Variable ventilation conditions have been tested by individually closing the complete or a partial set of holes on the outer square cylinder using an aluminium sheet. Thermal efficiency is determined using standard water boiling tests for all cases. A maximum thermal efficiency of 15.14 percent is achieved for the case with partial opening on the outer surface. Soot deposition on the vessel decreases as the air ventilation is increased. Emission in terms of CO and carbon-dioxide has been measured. CO shows a decreasing trend with increasing ventilation. Further, average flame heights have been measured during steady burning period. Furthermore, the total burn time and average mass burning rate of the wood are reported.

***Keywords*:** Wood stove; Casuarina wood; thermal efficiency; emission; flame height

1. Introduction

For domestic purposes such as cooking, heating, and boiling water, about 40% of the world's population rely on heterogeneous fuel combustion. These fuels include biomass, wood, charcoal, animal dung, crop residue and various other wastes. Furthermore, in developing nations such as India, wood and biomass typically accounts for more than 90% of total rural energy supply. According to the World Health Organization (WHO), each year around 1.5 million people die due to the exposure to smoke and other toxic pollutants produced by solid fuel combustion [1]. Furthermore, many people are affected by acute respiratory disorders. Women and children are the most vulnerable to the effects of cooking since they spend more time in that zone. Indoor smoke from solid fuels is one of the top ten health hazards, according to the WHO, and indoor air pollution is responsible for 2.7 percent of worldwide disease burden [2]. Raj et al. [3] compared the levels of indoor emissions in houses that used biomass and LPG fuels. The families using fuels such as coal, wood, cow dung, etc., had much higher indoor level pollution in terms of SO_2, NO_2, CO and other suspended particulate pollutants, than those use LPG stoves. In another study, Rosati et al. [4] reported that inhabitants of Ladakh, India, had higher levels of inflammatory cells, particulate matter, endotoxin, and carbon monoxide in their sputum. Singh [5] reported that using an improved cooking stove, the concentrations of all the gaseous pollutants as well as the amount of fuel consumed can be minimized.

Mamuye et al. [6] concluded that when compared to a traditional charcoal fired stove, a Merchaye stove resulted in reduced emissions of CO, CO_2, and PM 2.5 by around 28%, 22%, and 27%, respectively. In the case of the Lakech stove, CO, CO_2, and PM 2.5 levels were reduced by 15%, 8%, and 13%, respectively. Individual Merchaye stoves had a 0.33 tonne CO_2 equivalent annual emission reduction potential, while Lakech stoves had a 0.14 tonne CO_2 equivalent yearly emission reduction potential. Improved biomass cooking stoves can reduce interior pollution [7], black carbon and greenhouse gas emissions [8], as well as the time and money spent procuring and gathering fuel wood, as well as the demand on local fuel wood supplies [9]. According to a study [10], fuel consumption was 5.4 kg per day for rocket mud stove (stove made from clay mud) and 6.7 kg per day for a stove crudely made of three stones. Another study [11] reported that in traditional three stone stove, the thermal efficiency was somewhat higher than that of the Plancha stove (14.8% for traditional three stone as compared to 13.7% for Plancha stove). However, as compared to a regular three-stone fire, the Plancha improved stove produced significantly less CO and suspended particulate matter ($PM_{2.5}$). Rasoulkhani et al. [12] found that the improved stove had a higher thermal efficiency (35%) using typical Iranian biomass than the traditional three stone stove (12.6%). Berrueta et al. [13] investigated and analysed the energy efficiency of the upgraded Mexican wood-burning Patsari cook stove. When compared to a regular open fire, fuel wood savings in rural families were estimated to be between 44% and 65%. The average energy savings for families using fuel wood and LPG were 66 % and 64 %, respectively. Zuk et al. [14] evaluated the influence of the Patsari cook stove on indoor air pollution. They discovered that 48-hour mean $PM_{2.5}$ concentrations in residences that burnt wood in open flames were 693 g/m^3 near the stove, 658 g/m^3 in the kitchen away from the stove, and 94 g/m^3 on the patio. $PM_{2.5}$ concentrations were measured before and after the installation of a Patsari improved wood burning stove, and it was discovered that there was a 71% reduction in fine particulate matter concentrations near the stove area and a 58% reduction in kitchen concentrations, and the outdoor patio remained unaffected.

As discussed in literature survey, a lot of work has been done in past few decades on studying and modifying traditional cook stoves into improved cook stoves. Thermal efficiency and smoke emission have always been topics of concerns. Type of fuel (locally available) influences the performance. It is necessary to design and test a stove using locally available solid fuels. Thus, the main objective of this work is to design a wood stove for rural India, where Casuarina wood is available for usage. The performance of this stove has been evaluated systematically.

2. Experimental Set-Up and Procedure

Figure 1 shows the geometrical features of the wood stove. It has two concentric square cylinders. Outer cylinder has holes of 15 mm diameter drilled at a separation of 50 mm horizontally and 30 mm vertically on its surfaces. Inner cylinder has 13 mm holes drilled at horizontal separation of 35 mm and vertical separation of 24 mm. The front surfaces of both cylinders have openings with hemispherical shaped top portion to insert wood logs. The bottom surface, grate, has 16 holes of diameter 15 mm each. At least a 15 mm margin is given from the edge of the surface to the nearest hole periphery.

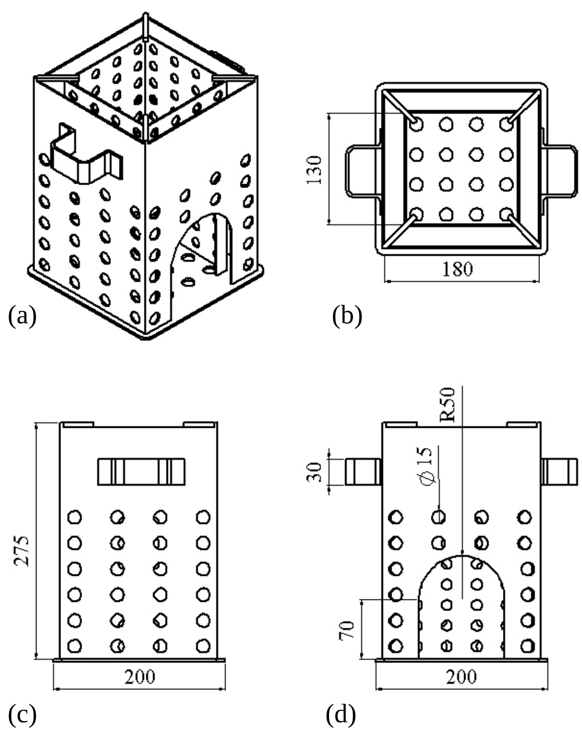


Fig. 1: Geometry of wood stove (a) Isometric view (b) Top view (c) Side view and (d) Front view. All dimensions are in mm

The height and the width of the rectangular portion are 120 mm and 100 mm, respectively and the semicircle on top has a radius of 50 mm. The wood stove is kept on the bottom support over a load cell, such that the grate is at 55 mm from the ground in all the experiments. Load cell, with maximum capacity of 10 kg and least count of 0.1 grams, is used to determine the mass loss of wood rate as a function of time. The air entrainment into the flame is always present from the bottom through the holes in the grate and through the front opening in all the experiments. Experiments are conducted with holes on the outer cylinder kept entirely open, partially open or entirely closed. Additional air ventilation occurs through the open holes of the outer surface. Therefore, based on the nature of the fuel, additional air requirement can be met with this design.

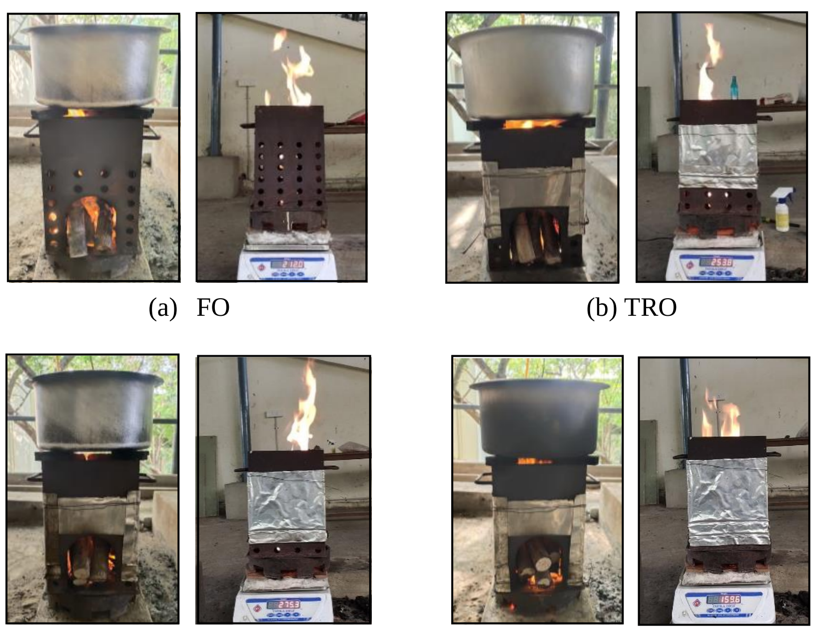
3. Results and Discussion

3.1. Thermal Efficiency

Four configurations are considered. In the first configuration, holes in the outer cylinder are kept fully open (FO). In the second, only one (the bottommost) row of holes in the outer cylinder is kept open (ORO). In the third, last two rows of holes of the outer cylinder are kept open (TRO). In the last configuration, all the holes of the outer cylinder are fully closed (FC). These are shown in Fig. 2, with vessel and without vessel. The thermal efficiency test is performed for these configurations. The percentage of total energy released due to the combustion of wood goes into heating water sensibly from the room temperature (27ºC - 30ºC) to a temperature of 95ºC (saturation temperature 100ºC) [15]. This is defined as thermal efficiency, expressed as,

$$\eta_{th} = \frac{m_w c_w \Delta T}{m_f CV} \quad (1)$$

Here, m_w is the mass of water (kg), c_w is the specific heat of water (kJ/kg-K), ΔT is the temperature difference (final temperature minus the initial temperature of water) (ºC), m_f is the mass of fuel burnt (kg) and CV is the calorific value of the fuel (kJ/kg). A vessel having a diameter of 245 mm and a depth of 130 mm is filled with 4.8 litres of water (as per BIS standard). Based on the air entrainment, the characteristics of the flame change, affecting the thermal efficiency.



(a) FO (b) TRO

(c) ORO (d) FC

Fig. 2: Experimental setup for different ventilation conditions of wood stove (a) FO (b) ORO (c) TRO and (d) FC

The total time taken to heat the water from the room temperature (27ºC - 30ºC) to a temperature of 95ºC is measured with a stopwatch. Each case is at least repeated for three times and the average values are reported. The mass of fuel burnt is determined using the initial and final masses recorded by the load cell in that duration. A maximum thermal efficiency of 15.14% (Fig. 3) has been obtained in the experimental setup for the case with last two rows of holes open on the outer cylinder (TRO). The thermal efficiency of 9.53% is obtained for the case with all holes on the outer surface kept open (FO).

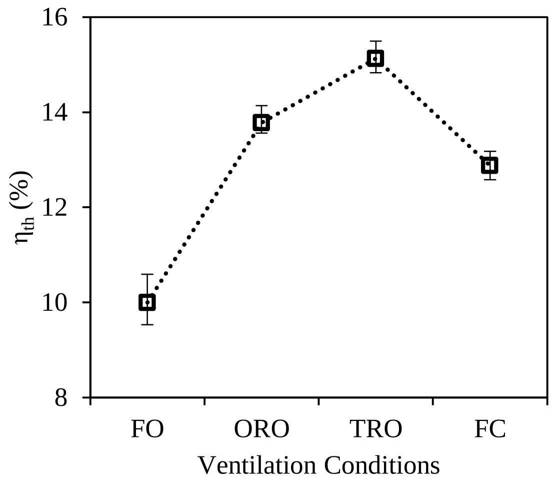


Fig. 3: Average thermal efficiencies for different ventilation conditions

Table 1 reports the time (in minutes) taken to heat the water, m_f, the quantity of fuel consumed (kg), and η_{th}, the thermal efficiency (%). As more holes are opened to the atmosphere, higher amount of air entrainment occurs, and three physical processes can take place. First, higher air entrainment can increase the burning rate and lower the emissions by oxidizing CO and particulate matters. Second, convective cooling can occur due to higher ventilation, causing a decrease in flame temperature, and therefore, the burning rate. This may also cause emissions to increase sometimes if incomplete combustion occurs. Third, hot gases can possibly escape through the open holes, affecting the heat transfer to the vessel, reducing the thermal efficiency. Thus, there are competing effects. These are also dependent on the nature of the fuel burnt. In this study, a favourable configuration to effectively burn the Casuarina wood logs and to achieve maximum possible thermal efficiency is obtained as TRO. The burning time of TRO configuration is lesser than that of FO configuration.

Table 1: Thermal efficiencies for different ventilations conditions.

Cases	t_{wb} (minutes)	m_f (kg)	η_{th} (%)
FO	33	0.717	10.59
	31	0.792	9.53
	35	0.766	9.86
ORO	25	0.559	14.14
	23	0.583	13.56
	25	0.580	13.63
TRO	26	0.525	15.05
	24	0.533	14.83
	23	0.510	15.50
FC	24.5	0.619	12.58
	26	0.591	13.18
	24	0.605	12.87

3.2. Flue Gas Analysis

The concentrations of CO_2 and CO in the gas phase have been measured for FC and TRO configurations during the the steady burning period. The gases are collected using a hood shaped like inverted funnel, cooled and sent to gas analyser analyser passing through a moisture trap. The concentration of CO (as is basis) is higher in the case of FC than TRO, as shown in Fig. 4a, due to lesser air entrained into the stove. The concentration of CO_2 released by TRO is also lesser than that that of FC case (Fig. 4b). The highest volumetric concentrations of CO_2 and CO in FC case are 7.26% and 0.18%, respectively, compared to 6.58% and 0.12% in TRO case. The average CO_2 concentration throughout the steady burning phase is 5.52% and 4.13%, respectively, for FC and TRO cases. Similarly, the average CO concentrations are 0.14% and 0.08%, for FC and TRO cases, respectively. The ratio of average volume percent of CO to that of CO_2 can represent a CO index. The ratio is 0.025 for FC configuration and 0.019 for TRO configuration, showing a lesser CO index for TRO configuration. Similarly, for FC case, the average oxygen volume percent ($\%O_2$) in flue gas is 16.7% and for TRO, it is 18.1%, showing higher amount of oxygen in flue gas. A quantity called CO-air-free is defined as $\%CO \times [21/(21 - \%O_2)]$. The average values of CO-air-free for FC and TRO are 0.69% and 0.57%, respectively, indicating a lesser CO-air-free index for TRO. Further, it is seen that the soot deposition on the vessel surface in TRO arrangement is much lower than that in FC configuration.

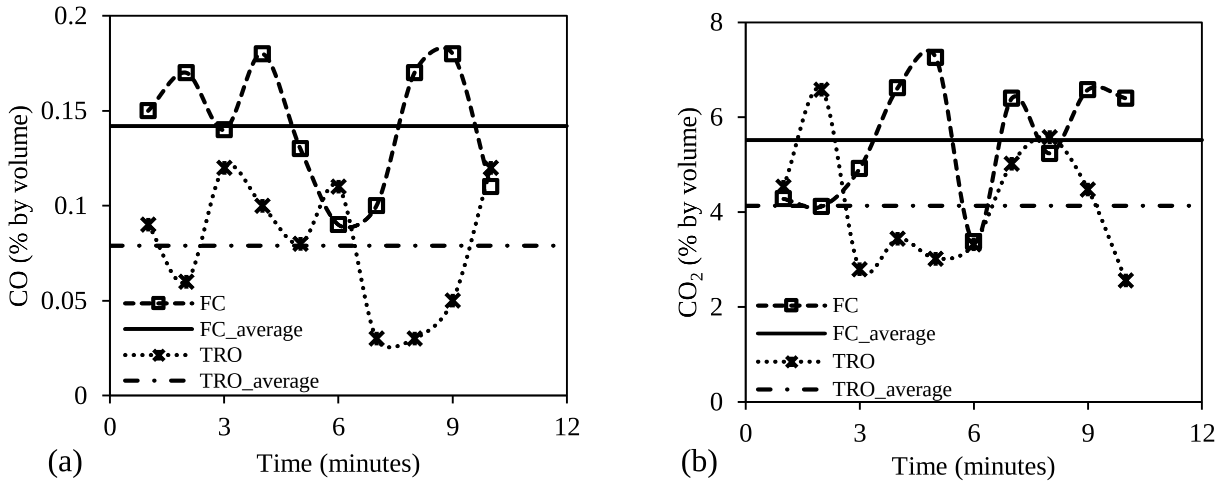


Fig. 4: Variation of CO_2 and CO during steady burning for fully closed (FC) and two rows open (TRO) cases

3.3 Mass Burning Rates

To determine the burning characteristics in all configurations (FO, TRO, ORO, and FC), Casuarina wood of a given initial mass (325 ± 5 grams) is loaded in the stove and burned without a vessel kept on the stove. Parameters such as mass burning rate, mass of air entrained and flame height have been studied. Burning duration continued till all the wood has been totally consumed. The mass burning rate of the fuel is determined by dividing the initial mass (final mass being zero) by the time taken for complete burning. Each test is carried out for three times. Figures 5(a) and 5(b) report the average burning duration and average mass loss rates, respectively.

The average total burning time have been 10.7 minutes, 12.2 minutes, 12.5 minutes and 14.8 minutes, for FO, TRO, ORO and FC configurations, respectively. The average burning period for FC is the longest because of slow air entrainment into the wood stove. The paths for air flow for this case are through the bottom grate holes and through the front opening used to load the fuel. On the other extreme, for fully open (FO) case, the burning time is the shortest for the same initial fuel mass, because of highest area available for air entrainment. For the cases with partially open holes on the outer cylinder (ORO and TRO), the average time for complete burning does not change much. The average mass loss (burning) rate (grams per minute) is obtained as 30.4, 26.6, 26 and 22, respectively for FO, TRO, ORO and FC configurations. The first effect of increased burning rate with higher ventilated area is seen.

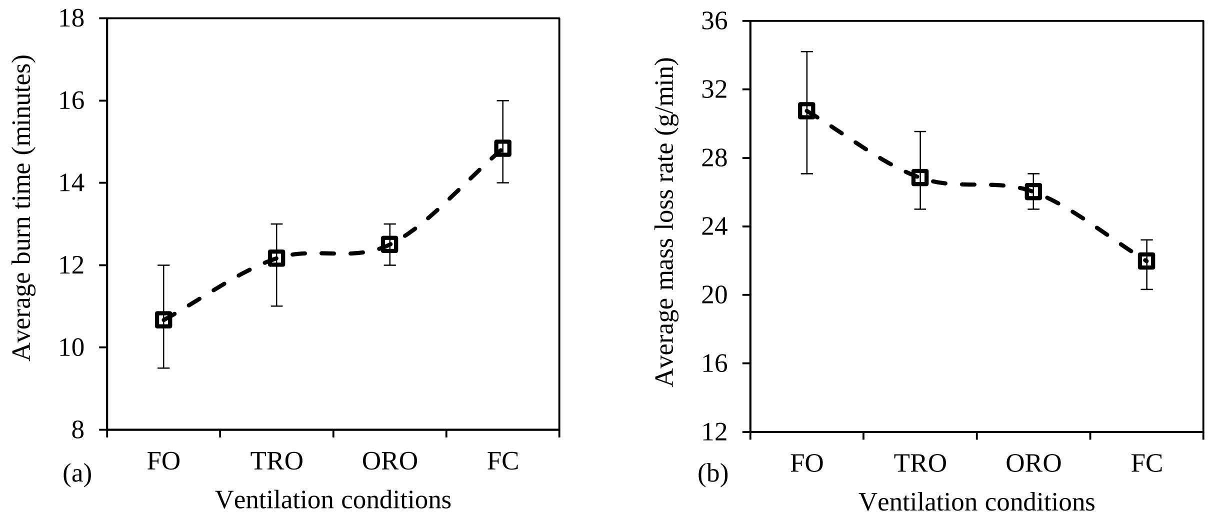


Fig. 5: (a) Average burn duration and (b) average mass loss rate for wood stove with different ventilation conditions

3.4. Flame Height

The instantaneous images obtained during the three trials of experiments on FO, TRO, ORO and FC configurations have been processed and the average flame heights, during the steady burning durations, are obtained. Figure 6 depicts the flame heights estimated from experimental data in comparison with the calculations using Heskested's correlation [16], which is expressed as,

$$H_f = 0.235\dot{Q}^{2/5} - 1.02D \quad (2)$$

Here, H_f is the flame height (m), $\dot{Q}$ is the heat release rate (kW) and D is the hydraulic diameter (m) of the exposed fuel surface. Results from Heskested's correlation match the experimental data with a maximum deviation of 12%, but within the experimental uncertainties. Uncertainties are higher indicating the puffing of the flames. The flame height for TRO is slightly higher than that in FO, and it decreases for and ORO and FC, which records the least height.

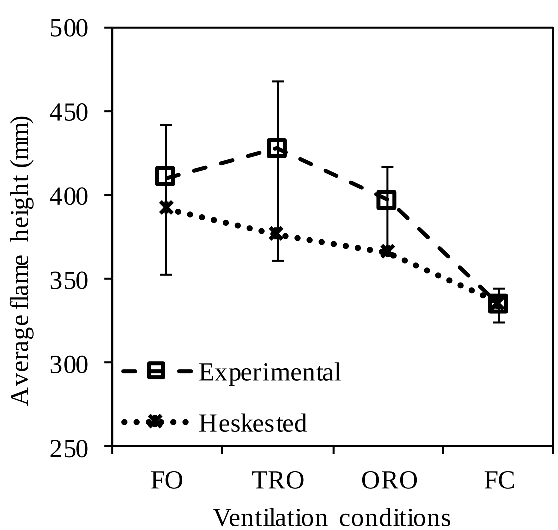


Fig. 6: Average flame height with different ventilation conditions

3.5. Air Entrainment

The air entrainment dictates heat release rate and flame height. It can be correlated using air properties, heat release rate and flame height, which are measurable, using Zukoski's correlation [17].

$$\dot{m}_a = E\left(\frac{g{\rho_a}^2}{c_p T_a}\right)^{1/3} \dot{Q}^{1/3} {H_f}^{5/3} \tag{3}$$

Here, $\dot{m}_a$ is the air entrainment rate (kg/s) into the flame, E is a constant (0.2), g is the acceleration due to gravity (m/s^2), ρ_a is the density of air (kg/m^3), T_a is the ambient temperature (K), $\dot{Q}$ is the heat release rate (kW) and H_f is the flame height (m). As shown in Fig. 7, the air entrainment rate decreases with a decrease in the ventilation.

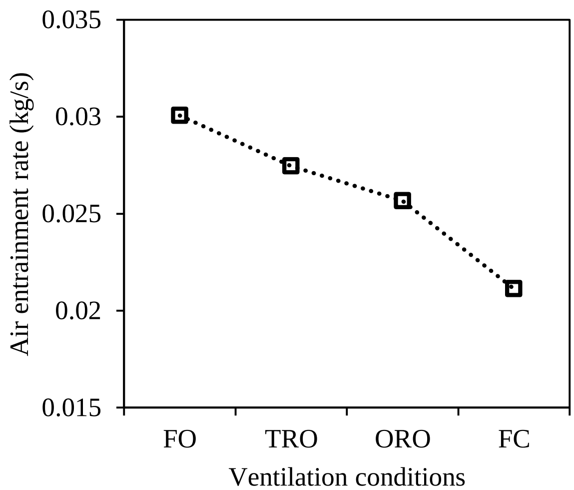


Fig. 7: Air entrainment rates for different ventilation conditions

4. Conclusions

An indigenous wood stove with two liner walls with several holes has been fabricated and tested for cooking application in rural areas in India. Thermal efficiency, emission, mass burning rate, flame height and air entrainment rate into the flame have been estimated and reported. Air entrainment (ventilation) to the flame is varied using four configurations, where the number of holes on the outer wall is kept open (FO), partially blocked (TRO, ORO) and completely blocked (FC). TRO configuration is seen to have the highest thermal efficiency (15.14%), followed by ORO, FC, and FO. The average mass burning rate decreases and the total burning time increases with a decrease in the ventilation. There is not much different in the burning rates of TRO and ORO cases. Comparing the emissions of TRO (with highest thermal efficiency) FC (with lowest thermal efficiency), the ratio of average volume percent of CO to that of CO_2, representing a CO index, is 0.025 for FC and 0.019 for TRO configuration. Similarly, the average values of CO-air-free for FC and TRO are 0.69% and 0.57%, respectively, indicating a lesser CO-air-free index for TRO. The soot deposition in TRO arrangement is much lower than that in FC configuration. The average flame height in FO is slightly lesser than that in TRO case. The least flame height is recorded for FC case, as a result of its lowest burning rate. Theoretical correlation for flame height is able to predict the trend quite well. Air entrainment into the flame in these four configurations has been estimated by a correlation based on heat release rate and flame height. As expected, a decreasing trend in the air entrainment is observed with decreasing ventilation. In summary, the indigenous wood stove is able to effectively burn Casuarina wood, available in rural areas. In TRO configuration, it produces low CO emission (CO air free around 0.57%) and low soot deposition on the vessel. A satisfactory value of thermal efficiency (15.14%), providing faster cooking time (24 minutes to heat up 4.8 litres of water from 25ºC to 95ºC), is also obtained.

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