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Design and performance analysis of institutional cooking stove for high hill rural community of Nepal

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Abstract

Increasing dependency on the firewood due to increasing population in the rural community of Nepal has result many adverse effects on energy, environment and human health. Due to large demand of energy, various technologies have been incorporated in stoves to increase its efficiency and reduce health risk. The paper focuses on design and fabrication of durable stove using proper orientation of insulating bricks considering technical, social and economic factor. A single pot institutional ICS designed with parameters under "Nepal Interim Benchmark for the Solid Biomass Cookstove 2016 protocols was fabricated and tested at Biomass Stove Testing Lab, Kathmandu University under "No wind condition". Total 12 bricks along with mild steel top plate of 3mm and proper insulated chimney were used to fabricate the stove. WBT were conducted under national stove testing protocol. Thermal efficiency, fuel consumption rate, burning rate, firepower and turn-down ratio are parameter used to determine the performance of the stove. Thermal efficiency was recorded 31% using *Alnus nepalensis*, a fuel, having the average moisture content of 13% on wet basis. The emission test was carried out using the Indoor Air Pollution Meter (IAP Meter) from Aprovecho Research Center, USA. The test was carried out along with the WBT test following the standard test protocols. The general average PM concentration was found to be 109 $\mu g/m^3$ and average CO concentration 3.6 ppm.

Keywords: ICS; chimney; draught; thermal efficiency; WBT; emission; IAP

1. Introduction

According the Government of Nepal, 4 out 5.4 million households in Nepal still rely on biomass as their primary cooking fuel and most of them still use traditional cooking stoves [1]. With the huge amount of firewood consumption, considerable amount of heat loss to ambient environment, high smoke production and improper draught system, traditional cooking stoves have been considered as inefficient. The use of efficient cooking stoves saves the fuel wood as well as it enhances effective burning with low emission to smokes. The thermal efficiency of the traditional cooking stoves accounts from 3% to 15% whereas the highest thermal efficiency of Improved Cooking Stove recorded at Biomass Stove Testing Laboratory, Kathmandu University is 31-32%.

According to World Bank report 2011, Improved Cooking Stove (ICS) is a stove that is designed to improve energy efficiency, lessen indoor air pollution, or lessen the time spent for cooking. Major benefits of ICS include increased thermal efficiency, less fuel wood consumption leading to reduced pressure on forest, clean indoor environment, convenience in cooking and cutting down the greenhouse gas emission. It reduces drudgery especially for woman and children, prevention of fire hazards. Some of the field test and measurement has shown that ICS saves about 50% fuel than traditional ones and reduces emission considerably.

The improved biomass cook stoves introduced in the study are modeled on the "rocket" stove, a key feature of which is a vertically elongated combustion chamber which controls airflow, combustion and mixing more than an open three-stone fire. Moreover, the walls of the combustion chamber are made of an insulating material with low thermal mass and the stove design directs the heated air and gases closer to the pot, increasing heat transfer [2]. Rocket stoves can range in size, materials, and portability, from small household models to large brick-lined institutional stoves, publicly available with the detailed design.

Indoor Air Quality (IAQ) refers to the air quality within and around the building that has an impact on its occupant. Indoor Air Pollution (IAP) is one of the biggest environmental problems especially in the developing countries where around 3 billion people cook and heat their homes using solid biomass. IAP is mainly increased by incomplete combustion, poor ventilation of room and improper draft caused by burning of solid biomass fuels like wood, dung, etc. Smoke from the wood burning is made up of a complex mixture of gases and fine, microscopic particles which has the biggest health threat. They are small enough to enter the lungs causing several diseases like bronchitis, pneumonia, asthma, and other serious respiratory diseases. These fine particles are also linked with the premature deaths in people aggravating for chronic heart and lungs problems [5]. Carbon monoxide (CO) is produced by the combustion sources and also may be introduced through the infiltration of CO from outdoor air to the indoor environment. Also, combustion of low grade solid fuel in the stove can cause high carbon monoxide emissions that might become lethal to the occupants unless the flue gases are vented outside via chimney throughout the cooking period. At the beginning, the pollutants released are dominated by the particulate matter (elemental and organic carbon) whilst carbon monoxide dominates in the end [4]. According to World Health Organization (2012), 4.3 million deaths are linked to indoor air pollution produced from inefficient stoves worldwide which is more than the death rate due to unsafe water [1]. The improved stoves use the smoke-hoods to draw smoke up and away from the home, reducing indoor smoke by 80%.

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When a fuel is being burned, it is important that sufficient time is available so that the fuel burns completely. Similarly, turbulence ensures a thorough mixing of the air and the fuel. If turbulence is not maintained, certain part of the fuel will have excess oxygen available for the combustion while the remaining have too little. Furthermore, if the temperature is not sufficiently high during the combustion, fuel will take some time to ignite thus increasing the time of the combustion. This will affect the heat output. As it can be seen, the 3T's can impact the process of combustion and can significantly affect the efficiency if not monitored closely.

The design and dimension of stove are calibrated for maximum transfer of heat of combustion from the flame and the hot gases to the cooking pot and minimum loss of heat to the surroundings. Better combustion of the fuel by providing an insulated combustion chamber around the fire, which leads to a better mixing of gases, flame and air. This enhances the temperature of the fire with the following consequences: faster water boiling, fuel use reduction, and decreases in CO and PM2.5. Heat in the chimney is not wasted; it is working hard to generate the draught which makes the fire hot and so release its maximum heat. Also proper draught in system pulls the air in to cause effective combustion and will carry away the waste smoke and gases. Grate is used just under the fire below primary air inlet.

The performance test of any stove can be done using different test: Water Boiling Test (WBT) with emission monitoring, Kitchen Performance Test (KPT) and Controlled Cooking Test (CCT). Standard protocol for lab based experiment is WBT. Based on national stove testing protocol design by AEPC Cold start, Hot Start and Simmering has been conducted. For the cold-start high-power phase, the test begins with the stove at room temperature and uses fuel from a pre-weighed bundle of fuel to boil a measured quantity of water in a standard pot. The hot-start high-power phase is conducted after the first phase while stove is still hot. The simmer phase provides the amount of fuel required to simmer a measured amount of water at just below boiling point for 45 minutes. The type, size and moisture content of fuel have a large effect on the outcome of stove performance tests. The emission test can be carried out with the WBT Test.

Jetter and Kariher [6] compared three-stone fires with improved stove types, measuring fuelwood consumption and pollutant emissions. The results of efficiency tests using the Water Boiling Test (WBT) protocol in different laboratories consistently show that most improved stoves have better fuel efficiency than three-stone fires. However, other investigations show that laboratory results from the WBT protocol gave little indication of how a stove would perform under typical cooking conditions in field settings [7]. Field-testing is therefore critical in estimating the achievable fuel saving of improved stoves.

2. Method

The WBT consists of a high-power phase and low power phase. It yields numerous indicators of stove performance but this report accounts parameters that are of particular importance to end-users and stove designers: time to boil a fixed quantity of water, burning rate, firepower, turn down ratio and thermal efficiency. The IAP Meter has a data collection sheet to record the data where, meter number, meter turn on date and time, background start and end time, test start and end time, and other detailed data about the test is recorded before starting the test. The real time emission exposure is monitored in the interval of 1 minute over the period WBT is started with the fire till the fire is extinguished. In addition, both qualitative and quantitative information about the stove, fuel and the test conditions should be recorded. These include:

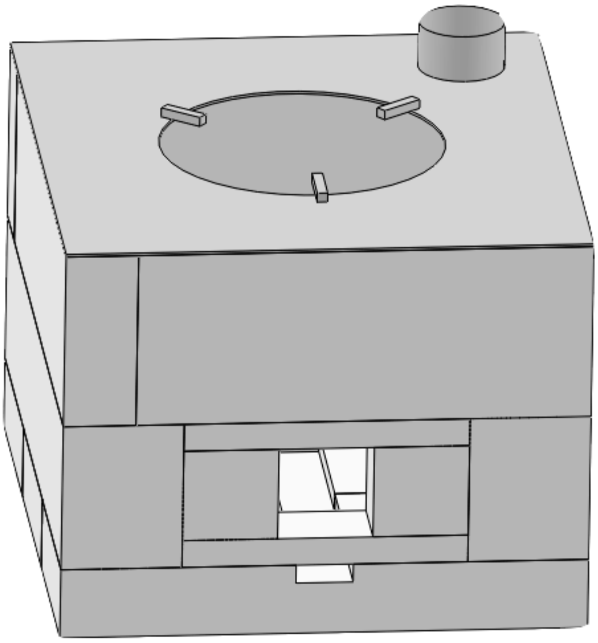

Figure 1: Cooking system design.

1. Air temperature
2. Initial water temperature
3. Wood Moisture Content (%-wet basis)
4. Dry weight of standard pots
5. Local boiling points of water

These parameters are recorded in the WBT data sheet along with the weight of the fuel wood to be used. Once these parameters are measured and recorded and the fuel is prepared, then the test proceeds [3].

The real-time pollutant concentrations were measured at 51 seconds interval over the combustion period during the WBT test. The IAP meter was turned on having set to 51 seconds mode and left in the clean environment for at least 10 minutes for the background adjustments. The meter was fixed with the pipe exposed to inhale the smoke produced and run until the fire was extinguished. The data stored in the SD card was downloaded to the computer and processed with the help of software designed to work with the Excel sheet provided with the IAP Meter [8].

2.1. Design specification of stove

The basic description of the fabricated stove is given as:

Length of Stove:	554 mm
Breadth of Stove:	612 mm
Height of Stove:	426 mm
No. of Pot Holes:	1
Chimney Diameter:	95 mm
Material of the Stove:	CLC Block
Inlet Size:	150×150 mm^2

The figure of prototype above shown is CAD design based on which the fabrication of stove for testing in BSTL, KU was designed. The design has a key feature of vertically elongated combustion chamber. There are two inlets provided: primary inlet for grate,

Figure 2: Working institutional ICS.

firewood, air and other for the air inlet only. The grate provides a certain height for the firewood since the fuel gets proper contact between the fuel surface and air to get completely combustion. Hence, the conductive heat loss to the ground decreases. Secondary inlet inclined at an angel of 45 degree lies just below the primary inlet which helps in pre-heating of air and mixing efficiently. Moreover, the walls of the chamber are made of an insulating material with low thermal mass and the stove design directs the heated air and gases closer to the pots, increasing heat transfer. The bricks are properly orientated with the objectives of minimum cost and maximum performance. Also it provides shielding around the fire and minimizes the radiative heat loss to the surrounding.

The Cellular Light Weight Concrete (CLC) Brickshaving dimensions 24×8×4 inch^3 and 24×8×6 inch^3 are used as a material to fabricate combustion chamber. These bricks are cut in their lengths with the adjustments to meet the required dimensions.

According to Nepal Benchmark for the Solid Biomass Cookstove, 2016 designed by AEPC, 3mm thick mild steel plate is used as a top plate with reinforcement to prevent hammering on it. Based on Standard Pot Selection Procedure for Testing Institutional Stove, the amount of water to be used during capital WBT testing shall be determined based on the burning capacity of the stove. While selecting the size of the vessel, the volume of water should not exceed 70% of the total volume of the vessel. The vessel determines the pot hole size of the stove. It consists of insulated chimney at the top face of the stove which provides natural draught. The chimney is insulated to keep the flue gases warmer, increase the upward speed of those gases and prevent condensation on the chimney.

3. Results and discussion

WBT consists of three phases that immediately follow each other: Cold Start, Hot Start and Simmering. While WBT, if the standard deviation for thermal efficiency deviates from more than 2%, test is re-performed.Test is performed in "No wind Condition" and fuel used for testing is *Alnus nepalensis* with wood moisture content in "%-wet basis". These different mode of test (Cold Start, Hot Start and Simmering) conducted are highlighted with blue, red and green bars respectively in the graph below for different result.

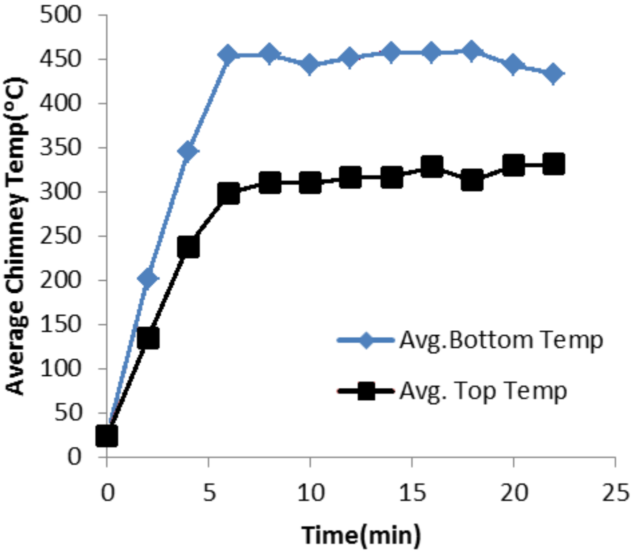

Figure 3: Average chimney temperature versus testing time at different position of chimney.

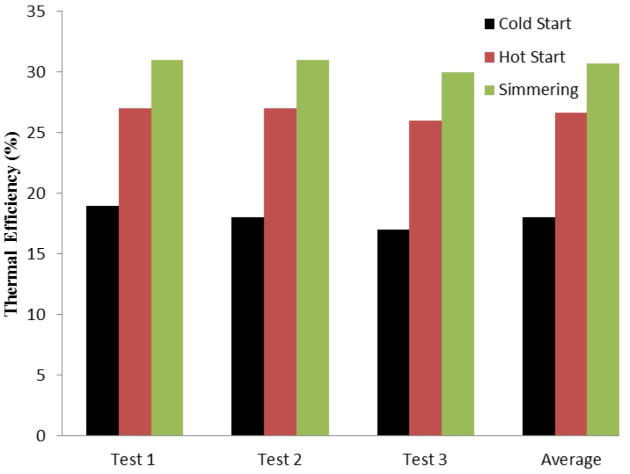

Figure 4: Cooking thermal efficiency.

The temperatures inside the insulated chimney are measured with k-type thermocouple at top and bottom with height difference of 2.5m. The graph of chimney temperature vs time with respect to the position is shown in Fig. 3.

The above figure shows that the temperature rises sharply from the ambient temperature as the combustion is started and then remains almost constant until the fire size is reduced. The chimney temperature decreases as we move higher due to heat transfer by flue gases to the chimney walls as it exits. The maximum temperature measured for bottom and top of the chimney are 548 ºC and 471 ºC respectively.

3.1. Cooking Efficiency

Thermal efficiency is a measure of how much energy in the wood fuel is transferred into the cooking pot.

The plots for thermal efficiency of the stove are measured in three different modes of WBT phase for each test is shown in Fig. 4. The general range of cooking efficiency in cold start (high power) test were found to be 17-19%, with the 18% average value and standard deviation of 1%. In hot start (high power) test, general cooking range recorded was 26-27% and in average 27% with 1% standard deviation. Similarly, in simmering (low power), the recorded range of cooking efficiency was 30-31% with average value of 31%

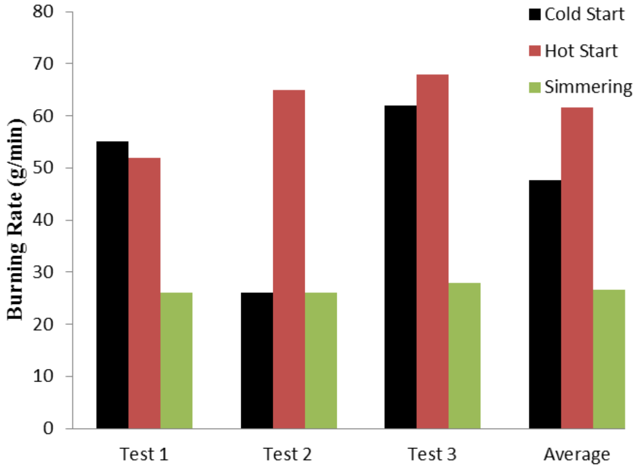

Figure 5: Burning rate.

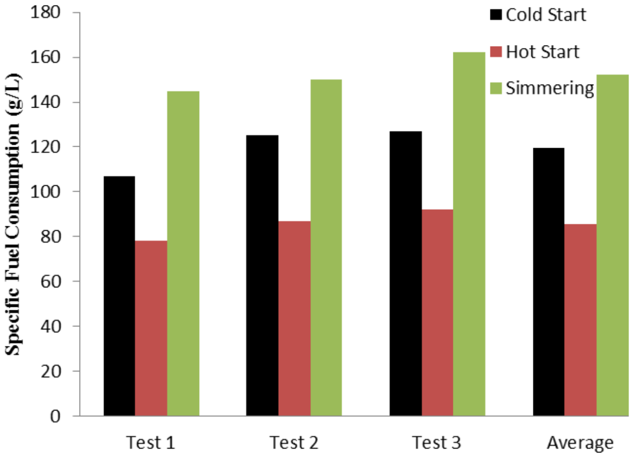

Figure 6: Specific fuel wood consumption.

and standard deviation of 1%. The stoves at simmering have higher efficiency rather than cold start as the system absorbs some amount of heat at the beginning.

3.2. Burning Rate

Burning rate is a measure of the rate of wood consumption while bringing water to a boil.

Fig. 5 shows that the stove has the highest burning rate at hot start more than simmering and cold start at three different tests. The highest burning rate was recorded in hot start with a figure in average of 61.7 g/min. Similarly, the lowest figure was recorded in cold start and simmering with figure of 57.7 g/min and 26.9 g/min in average with standard deviation of 3.9 g/min and 1.2 g/min respectively.

3.3. Specific Fuel Consumption

Specific fuel consumption is the fuel used per unit of product produced.

Fig. 6 indicates the obvious consumption of fuel-wood much higher in simmering and minimum in hot start. The average specific fuel wood consumption was recorded in Cold start, Hot start and Simmering was 119.7, 85.7 and 152.4 g/L with average standard deviation of 10.7 g/L, 7.2 g/L and 9.1 g/L respectively. The reason behind the high fuel consumption in simmering is because of continuous boiling of water for around 45 min to measure thermal efficiency of the stove.

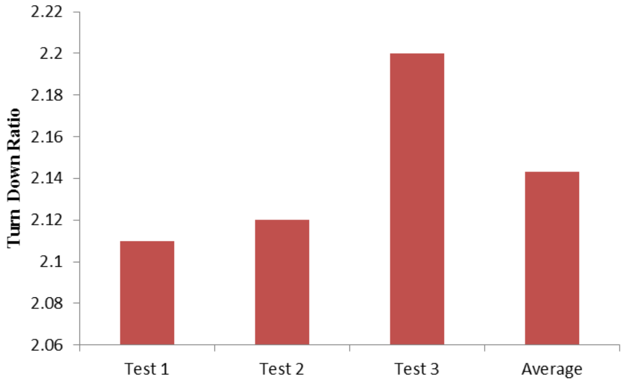

Figure 7: Turn down ratio.

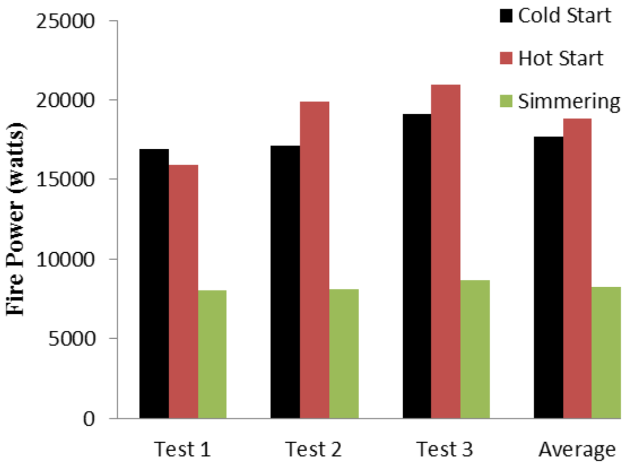

Figure 8: Fire power.

3.4. Turn down Ratio

Turn down ratio is the ratio between the high and low firepower and is the measure of how well the stove can be turned down from high to low power.

The turn down ratio for IICs varies from 2.11 – 2.20 in simmering of 45 min in time period with average recorded value of 2.14 with zero standard deviation from the three different test plotted in Fig. 7.

3.5. Firepower

Firepower is the measure of how much energy is released each second.

From Fig. 8, the average firepower in High power test i.e. cold start and hot start was 17,786 W and 18,962 W respectively. Similarly, firepower in low power test i.e. simmering recorded was 8,263 W. The reason behind high firepower in cold and hot start is that more energy is required to quickly boil water than to simmer water.

3.6. Stove Emission

Emission measurement measures the indoor air quality during the burning of firewood in the stove. The graph represents a time series emission exposure profile with the lab based WBT test conducted at BSTL Lab in the “No Wind Condition”. The graph indicates the start of the period for assessing background levels and testing the cooking period.

From Fig. 9, the general average PM concentration was found to be 109 $\mu g/m^3$ and average CO concentration was 3.6 ppm. Similarly, highest PM concentration was calculated to be 965 $\mu g/m^3$

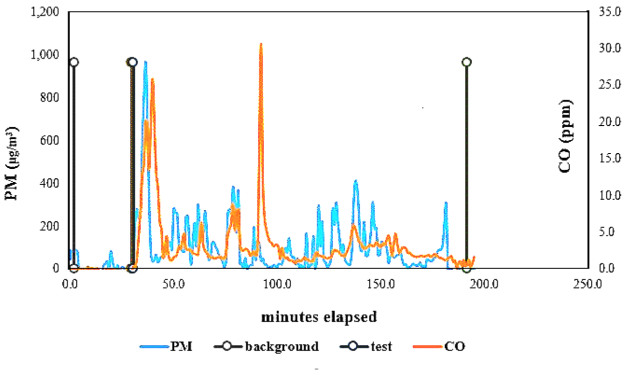

Figure 9: Emission exposure profile of PM and CO.

Table 1: Indoor Air Quality Standard 2009.

Pollutant	Maximum Concentration	
	Average Time	Level
$PM_{2.5}$	24 hours	60 $\mu g/m^3$
	1 hour	100 $\mu g/m^3$
CO	24 hours	9 ppm (10 mg/m^3)
	1 hour	35 ppm (40 mg/m^3)

and highest CO concentration was found to be 30.6 ppm during the test period. The real-time mean averages (μ) and standard deviations (σ) of $PM_{2.5}$ and CO concentrations during the WBT lab test periods were μ = 90.457 $\mu g/m^3$ (σ = 131.628 $\mu g/m^3$) and μ = 3.009 ppm (σ = 4.14 ppm) respectively. The National IAQ Standard and Implementation Guideline (2009) have set limitations for the pollutants as shown in Table 1.

However, average $PM_{2.5}$ concentrations still exceed the WHO indoor air quality thresholds for $PM_{2.5}$ and national air quality guidelines.

4. Conclusion

The model is fabricated with the aim to decrease the problems like indoor air pollution, excessive firewood consumption and excessive production of $PM_{2.5}$, CO_x, and NO_x etc. Using CLC blocks as an option of insulating materials makes the model easily manufactural, socially viable, aesthetically desirable and economically affordable. The use of this insulating material is highly recommended due to its low thermal mass, light weight, ease of working and eco-friendly which prove it as a significant solution. With successive iteration in its design, dimension, various tests and analysis discussed above infer that the fabricated model turns up to be more economic (optimized design and lesser fuel wood consumption), thermally efficient (in terms of simmering, hot start and cold start) and better in performance (fire power graph) with 31% thermal efficiency. The stove emission was measured for $PM_{2.5}$ and CO with average value of 109 $\mu g/m^3$ and 3.6 ppm respectively. Thus, the result shows that the stove is efficient in ways, fuel efficiency and emission criterion.

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