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Comparative study on performance and design optimization of natural draught institutional improved cooking stoves

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Abstract

Biomass is one of the major sources of domestic energy in rural part of developing countries. The use of efficient improved cooking stove over inefficient traditional stoves plays a pivotal role in reduction of pollutants and has a greater impact on environmental and human health. This paper aims to analyze the performance of natural draught institutional improved cooking stove in terms of thermal efficiency and pollutant emissions. Two stoves with varying design and dimension were constructed and given name as Prototype I (P-I) and Prototype II (P-II). Thermal efficiency and other performance parameters were analyzed following Water Boiling Test. The particulate matter of aerodynamic diameter of less than 2.5 μm ($PM_{2.5}$) and carbon monoxide (CO) was monitored for both prototypes. P-II performed better than P-I in terms of both thermal efficiency and pollutant emissions. The thermal efficiency of P-II was 31% which was nearly 2 fold higher than that of P-I. Similarly, emission of CO (4.6 ppm) and $PM_{2.5}$ (174 μg/m^3) in P-II was found to be reduced by ~50% and ~75% respectively. This study suggests that minor changes in design and dimension improves the performance of improved cook stove that may have substantial implications on energy, environment and health.

Keywords: Biomass; Improved cooking stove; Thermal efficiency; Water boiling test; Emission

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1. Introduction

Biomass is a term for every organic matter which is derived from animals and plants and the utilization of those matters for generation of energy such as for heat, electricity is called bioenergy [1,2]. Biomass fuel is a source of domestic energy for over 2.5 billion people worldwide [3]. It is the largest source of renewable energy accounting for around 66% of the total renewable energy supply [4]. Biomass fuel consumption is more prominently in rural part of the world that accounts for over 95% of fuel usage. Easy accessible to biomass fuel with no cost, low availability of renewable sources of energy like solar, wind and poor socioeconomic status for the affordability of alternative sources of clean energy like electricity, LPG are the determinants for the rapid increase in biomass fuel users. Hence, traditional biomass including wood, animal dung, crop residue and charcoal has dominated the energy consumption in low and middle income countries including Nepal [3].

Characterized with diverse geographical situation and accompanied by wide range of climate, Nepal is a suitable country for the booming of bioenergy [5]. Around 77% of total energy consumption in Nepal is fulfilled by biomass fuel out of which more than half of consumption is met by the fuel wood alone [6]. Approximately 11 million dry tons of fuelwood is consumed at the household level only for cooking purpose [7]. Combustion of biomass fuel for cooking is usually performed in a traditionally constructed inefficient cooking stove (Fig. 1) with poor ventilation in rural setting. Use of such stove having low thermal efficiency of 5-15% results incomplete combustion of the fuel that leads to formation of significant amount of undesirable gases like carbon monoxide (CO), nitrous oxide (N_2O), methane (CH_4), polycyclic aromatic hydrocarbon (PAHs), particles containing elemental carbon and other organic compounds [8,9]. This is the major source of household air pollution (HAP) and exposure to such noxious pollutants increases the risk of several chronic lung diseases and respiratory infections among adults and children [10]. HAP is accounted to have an estimated 4.3 million premature deaths each year worldwide that includes 21,000 premature deaths yearly in Nepal alone [11]. In addition to the effects of HAP on human health rapid deforestation associated with increased biomass need is another biggest environmental concern in the world and Nepal [12]. Though the percentage of people using biomass is in decreasing tread due to rapid urbanization, the absolute number of people using biomass fuel remains the same and will be the major source of energy for cooking for another 20 years. Several interventions have been proposed by national and international development organizations to the address this problem of energy poverty in Nepal as well as several other low incomes countries of Asia, Africa and Latin America. Improvement on the traditional stove design and use of improved cook stove (ICS) has been suggested as a prominent intervention to solve this problem until it is made possible for the easy accessible and affordable of clean cooking solutions to all [13].

The realization that improved cooking stoves being able to counter the adverse effect of biomass consumption led to several ICS programs in most developing countries of the world [8]. Here, the benefits of improved cooking stove can be generalized into two categories; Internal to the household which is money and time saved on acquiring fuel, reduced percentage of HAP, and various conveniences in use and external to households which is principally, diminished pressure on forest and energy resources and reduced greenhouse gases. As mentioned above, the main direct beneficiaries of the programs are the one who suffer mostly due to traditional cooking stove i.e. women and children in developing coun-

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Figure 1: Common traditional cooking stove used in Nepal.

tries [14]. The advantages of improved cooking stove are immense as it can be used in both household as well as commercial activities. Improved cook stove that can be used for larger scale in various institutions like school canteen, military canteen, jai have been designed and tested. The main purpose of this study was to analyze the performance and emission of newly designed institutional improved cooking stove and to see the variations in performance and emission by varying design and dimension. High efficient, low emission, low cost, easily manufacturable, quality and aesthetically desirable institutional improved cooking stove which provides a good option for cooking and heating purpose by reducing fuel consumption had been proposed as an outcome of this study.

2. Materials and method

This is a lab based experimental study which was carried out at Biomass Stove Testing Laboratory, Department of Mechanical Engineering at Kathmandu University Nepal. All tests were carried out in a control environment with no wind condition following the national testing protocol setup by Alternative Energy Promotion Centre [15]. Commonly used fuel wood "Pinus Roxburghi" with an average moisture content of 15% on wet basis (recommended in protocol) was used for all experiments. Two version of natural draught institutional improved cook stove has been designed and manufactured at technical training centre of Kathmandu University by undergraduate Mechanical Engineering students. The material used for the construction of these stoves was Cellular Light Weight Concrete (CLC) blocks. The performance analysis of both designs was carried out in terms of thermal efficiency and emission following a standard water boiling test (WBT). A given set of protocol for WBT was followed for the performance analysis where as additional low cost portable exposure monitor was used to measure $PM_{2.5}$ and CO during the test.

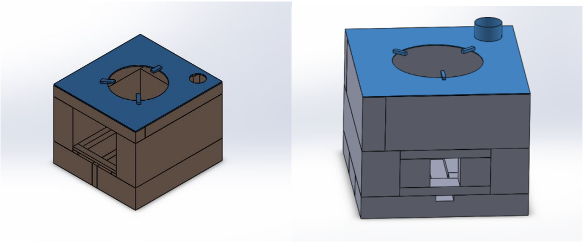
2.1. Stove design

Prototype I shown in Fig. 2a consist of inlets at the front and chimney at the top right face of the stove. There are two inlets provided to the stove: one is in front of the stove another is just below the feed hole with the surface angle of 100° to the horizontal. This design of stove consists of a natural draught system to draw air inside the combustion chamber for the combustion of fuel wood. The chimney directs exhaust gases out of the combustion chamber and provides necessary draught to draw the air into the combustion chamber. The chimney is placed at the upper right corner of the top face. The burning woods are pushed into the fire as they burn and, in this process, coals are formed.

Prototype II shown in Fig. 2b consists of the inlet at the lower side and chimney at the top face of the stove. There are two inlets provided: one for grate, firewood, air and other for the air inlet only. The grate provides a certain height for the firewood since the fuel get proper contact between the fuel surface and air to get complete combustion. Hence, the conductive heat loss to the ground decreases. The chimney, insulated with ceramic blanket, is provided to make smoke free kitchen and provides necessary draught to draw the air into the combustion chamber. The chimney is placed at the corner at the top face.

Table 1: Dimensional parameters of the cooking stoves.

Parameters	Dimensions	
	Prototype I	Prototype II
Length of Stove	430 mm	555 mm
Breadth of Stove	460 mm	610 mm
Height of Stove	460 mm	430 mm
No. of Pot holes	1	1
Chimney diameter	64 mm	95 mm
Inlet Size	230 × 200 mm^2	100 × 100 mm^2



(a) Prototype I (b) Prototype II

Figure 2: Design of (a) Prototype I, and (b) Prototype II with CLC as an insulating brick. The brick orientation in both prototypes is different with the variations in stove dimension. The dimensional variations in both prototypes are presented in Table 1.

Both prototypes were designed for standing mode of cooking with CLC block as an insulating material. The prototype design was mainly focused on main concept behind the design on these stoves was how to construct the prototype with less number of bricks, focusing on stability and strength of the system. Also, cost can be reduced if number of bricks used was less. With the variation in dimensions of the stove, the cost of top plate made up of mild steel with 2mm thickness can also be reduced. The size of primary air inlet and fuel inlet door size was considered as major changes in both prototypes. The dimensional parameters of both prototypes are presented in Table 1.

2.2. Water boiling test

The Water Boiling Test (WBT) is a simplified simulation of the cooking process [16] normally carried out to analyze stove performance in a controlled environment. It is intended to measure how efficiently a stove uses fuel to heat water in a cooking pot and the quantity of emissions produced while cooking. It is thus a convenient method for the comparison of the stoves [17]. The WBT consists of three phases: Hot Start, Cold Start and Simmering that immediately follow each other. A full WBT test should always include all three test phases and should be conducted at least three times for each stove, which constitutes a WBT test set. Firstly, during the cold-start phase, the stove is turned on at room temperature and a specific quantity of fuel is used to boil a measured quantity of water in a standard pot. Then the boiled water is replaced with a fresh pot of ambient-temperature water to perform the second phase. Then, the hot-start phase is performed immediately after the first phase keeping the stove hot. Again, the specific quantity of fuel is used to boil a measured quantity of water in a standard pot. On repeating the test with a hot stove, it provides us a valid information to identify differences in performance between a stove at low and high temperature. This is specifically important for stoves with high thermal mass as these stoves are generally kept warm in practice. Finally, the simmer phase determines the quantity of fuel needed to simmer a measured amount of water at just below boiling point for 45 minutes [18]. As biomass burning is a highly variable process, the type, size and moisture content of fuel have a large effect on the outcome of stove performance tests [19]. For that reason, all tests of a single stove, or all tests to compare designs or stoves, must is done with fuel of the same type and moisture content, and similar size.

2.3. Emission test

Real time emission of $PM_{2.5}$ and CO from the combustion of fuel wood during the conduction of WBT for both stove designs was monitored. The emission was measured per task that is the total pollutants leaving the stove were monitored for each WBT test. The emission was monitored using an Indoor Air pollution (IAP) meter which is a simple easy to use low cost sensor aerosol mass monitor. With inbuilt sensors for $PM_{2.5}$ and CO, IAP meter can log continuous real time emission of $PM_{2.5}$ and CO during the test period. The CO sensor is an electrochemical cell with a range of 0–1000 ppm whereas PM sensor is a red laser light scattering photometer which has a range of 0–60000 $\mu g/m^3$. There are several experimental settings where the IAP meter can be used [20]. An average concentration of CO and $PM_{2.5}$ was measured during the test to compare the emissions from each stove.

2.4. Experimentation

A prototype of both stove designs was manufactured as per the design parameters and installed at the biomass stove testing lab for the experimentation. A set protocol of WBT was followed to measure the performance parameters of both stoves that included thermal efficiency, fire power, burning rate, specific fuel wood consumption and time to boil water The thermal efficiency (η), burning rate (r_b), specific fuel consumption (SC) and fire power (P_F) was calculated using Equations 1 to 4 respectively.

$$\eta = \left[\frac{(C_p W_1 (T_1 - T_w) + E_v W_e)}{(E_f W_f) - (E_k - W_k)} \right] \times 100 \tag{1}$$

$$r_b = \left(\frac{W_f}{T} \right) \times 100 \tag{2}$$

$$SC = \frac{W_f}{T_{fc}} \tag{3}$$

$$P_F = \frac{(E_f W_f)}{T} \tag{4}$$

where C_p is specific heat of water, W_1 is weight of water in pot, T_1 is temperature of water boiling in pot, T_1 is temperature of water at the start of boiling, E_v is latent heat of vaporization of water, W_e is weight of water evaporated at the end of the test, E_f is heating value of fuel, W_f is weight of fuel used, E_k is heating value of charcoal, W_k is weight of charcoal remained, W_f is weight of fuel used, T is time taken to complete the task, T_{fc} is total food cooked [18].

The above performance parameters for each stove was calculated for all three phases of WBT, cold start, hot start and simmering phase and compared for both stove prototypes. Emission of $PM_{2.5}$ and CO per task was monitored for each WBT test for both stoves under the same conditions. The IAP meter was turned on at the start of the WBT and turned off after the completion of all three stages of the test. The data presented for emission was the average concentration of all three test phases. Three complete sets of WBT was carried out and the data for both performance and emission matrix was the average of three complete test. A complete WBT test means repeat of each test (including all three phases of WBT) three times.

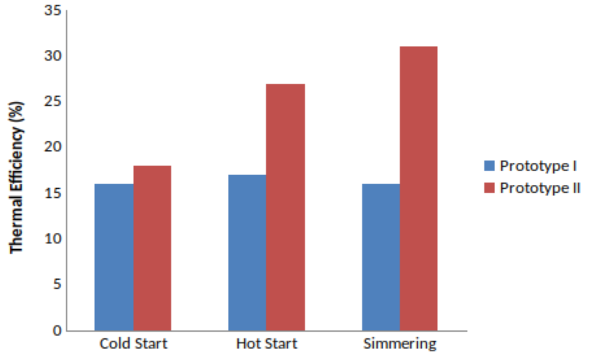


Figure 3: Thermal efficiency of the prototypes for all the phases of WBT.

3. Results and discussion

All tests were carried out in a similar control laboratory settings using same fuel wood. The average consumption of fuel for each test was 997 mg of the wood and the pot used as of flat aluminum bottom capable of holding up to five liters of water. The average time required for the completion of all three phases of one set of WBT was about 120 minutes. A total of three consecutive tests were carried out for both prototypes and the result presented was the average of all tests.

3.1. Thermal Efficiency

The result showed that stove characteristic, performance matrix and emission matrix was better in prototype II than in prototype I. The thermal efficiency of prototype I and prototype II for all three phases of WBT is presented in Fig. 3. Thermal efficiency of prototype I and prototype II remained the same during the cold start phase. There was no improvement on thermal efficiency of prototype I during hot start and simmering phase which remained the same at about 16-17%. Whereas the thermal efficiency of prototype II increased from 18% during cold start to 27% and 31% during hot start and simmering phase respectively. This shows that under similar test condition the thermal efficiency of prototype II is nearly 2 fold higher than the thermal efficiency of prototype I during hot start and simmering phase.

3.2. Boiling time

The average water boiling time for both prototypes during cold start and hot start is presented in Fig. 4. For both prototypes the average water boiling time was less during hot start (24.3 minutes in prototype I and 15.2 minutes in prototype II) then in cold start (34.3 in prototype I and 22.7 minutes in prototype II). This is an obvious observation as hot start phase is started immediately after cold start where stove is already in certain high temperature. It is observed that prototype II takes less time to boil the same amount of water than prototype I for both cold and hot start.

3.3. Specific fuel consumption

The specific fuel consumption for prototype I and prototype II during all three phases of WBT is presented in the Fig. 5. The amount of fuel required to boil 1 liter of water during the test was less in prototype II as compared to prototype I for all phase of WBT. Average specific fuel consumption for prototype II during cold start, hot start and simmering was 119.7 g/L, 85.7 g/L and 152.4 g/L which was about 73% less than prototype I for all respective phases. For both prototype the fuel consumption was high in simmering phase because boiling of water takes place continuously for around 45 minutes at a constant temperature.

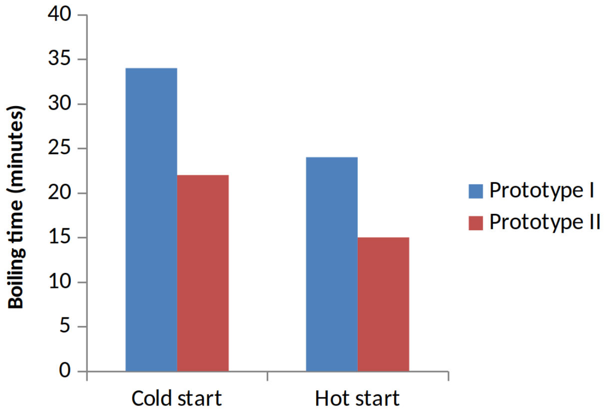


Figure 4: Boiling time of the prototypes.

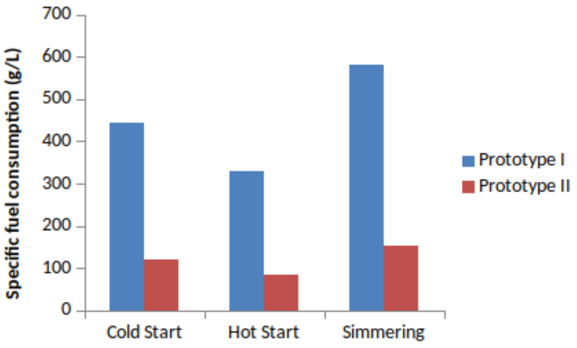


Figure 5: Specific fuel consumption in (g/L) of the prototypes for all the phases of WBT.

3.4. Burning rate

Fig. 6 shows burning rate of prototype I and prototype II for all three phases of WBT. It was measured to observe the rate of fuel consumption while bringing water to boil. It indicates how efficiently a stove burns the fuel during cooking. Higher burning rate was observed for prototype II as compared to prototype I for all three phases of the test that indicates efficient and consistent burning of fuel in prototype II than in prototype I. This also supports the less boiling time observed for prototype II. The burning rate for prototype II was 61.7 g/min, 57.7 g/min and 26.9 g/min whereas the burning rate of prototype I was 27.16 g/min, 26.3 g/min and 15.4 g/min during hot start, cold start and simmering respectively.

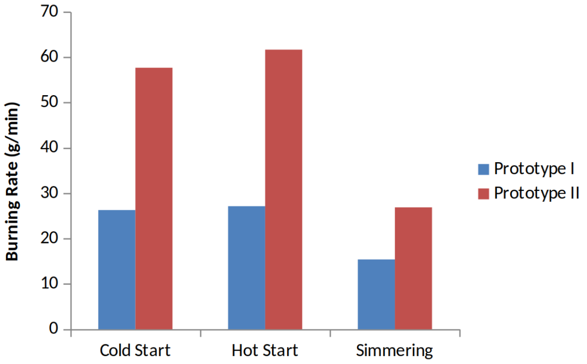


Figure 6: Burning rate in (g/min) of the prototypes for all phases of WBT.

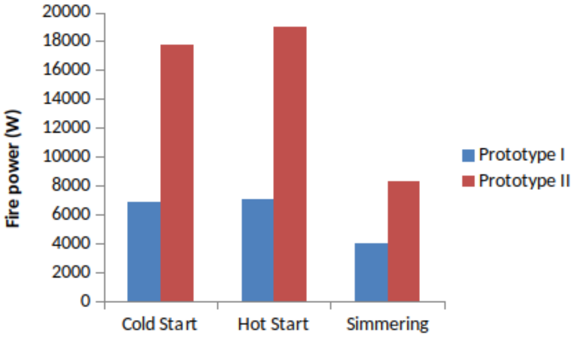


Figure 7: Fire power (W) of both prototypes for all phases of WBT.

3.5. Fire power

The firepower for both stoves during the test is shown in Fig. 7. It indicates the stove heat power and provides an indication of how quickly fuel was burning. As this parameter mostly depends on stove size, it is an obvious observation that fire power for prototype II was higher than prototype I. The highest firepower (18962 W) was observed for prototype II during hot start which was followed by cold start (17786 W) and simmering (8263 W) respectively. As more energy is required to boil water in cold and hot start as compared to simmering phase, firepower in hot and cold start is higher than simmering phase for both prototypes.

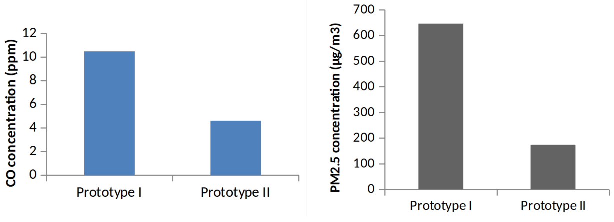
3.6. Emission matrix

The emission of CO and $PM_{2.5}$ was monitored during the test for both prototypes to compare the emission matrix. Average concentration of CO and $PM_{2.5}$ for all tests for prototype I and prototype II is presented in the Figs. 8-a and 8-b respectively. The result showed that prototype II emitted less concentration of both CO and $PM_{2.5}$ as compared to prototype I. Average CO concentration of 4.6 ppm was observed from the prototype II which was about 55% less that that emitted from the prototype I. Similarly, the overall percentage reduction of $PM_{2.5}$ emission from prototype I (645.6 $\mu g/m^3$) to prototype II (174 $\mu g/m^3$) was 73%. This result indicates that prototype II is better in terms of less polluting stove. Though the emission in this study was monitored only for test period, the average $PM_{2.5}$ concentrations from prototype II still exceed 24 hour average indoor concentrations recommended by WHO and 1 hour average indoor concentration of national air quality guidelines.

In prototype II the primary air inlet was designed with 45 degree of inclination which creates good natural draught in the system enhancing proper combustion and extraction of energy from the fuel. Increased in combustion efficiency reduces the emission and better extraction of energy from the fuel enhances the thermal efficiency of the system. In addition to this change in orientation of the CLC block in the combustion chamber creates good turbulence and increases the temperature of flue gases in the system. Also retention time of gases inside the chamber improved the performance of time to boil water and fuel wood consumption. Overall the 3T (Time, Temperature and Turbulence) factors were better in prototype II compared to prototype I.

4. Conclusion

This study was carried out to see the effect of design and dimension optimization on performance and emission of improved cooking stove. For the study, the cooking stove models were constructed as per design with proper instrumentation and experimentation and the lab based experiments were performed under



(a) (b)

Figure 8: Average emission concentration from prototype I and prototype II. (a) CO concentration, and (b) $PM_{2.5}$ concentration.

the constraints as per national testing protocol by Alternative Energy Promotion Centre, Nepal. The result from the study shows that prototype II of natural draught institutional improved cooking stove is much more efficient than prototype I in terms of both performance and reduction in emissions. The study signifies the concept of design optimization and its capacity to augment the efficiency and improve the performance of the system. As the result presented in this study is solely based on controlled lab experiments the conditions might change when measured under real cooking condition. It is hence recommended to perform more experiments to understand how stoves perform with real cooking environment with local foods and varying cooking practices. In addition to this, though there is an increase in efficiency and reduction of emission level by modification on size and dimension of the stove there is a plenty of room to play on design to increase more efficiency and reduce the emission level below the WHO recommended safe level. However as based in the result of this study which showed around fifty percent improvement on efficiency and seventy percent reduction in emissions, the use of Prototype II is to be encouraged over prototype I for the better energy usage and emission control.

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