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Bangladesh J. Sci. Ind. Res. **49(4),** 219-226, 2014

BCSIR

BANGLADESH JOURNAL OF SCIENTIFIC AND INDUSTRIAL RESEARCH

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Performance evaluation of improved cook stoves (ICS) disseminating in Bangladesh

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Abstract

This paper describes the monitoring and evaluation of three improved cook stove (ICS) provided by GIZ, which were they disseminated throughout the Bangladesh. The project assessed stove performance using lab-based water boiling tests (WBTs), which yield a number of performance indicators including time to water boil, specific fuel consumption, average fire power and energy efficiency when the stove is operated at both high and low power output. In all cases, ICSs were compared to local traditional cook stoves (TCSs). The results of the WBTs were mixed. Although the improved stoves generally showed some improvement in efficiency for the low-power simmering phases, the stoves were less efficient than traditional stoves in high-power water-boiling phases. Three ICS models and one traditional stove were tested and compared. Results from this study provide stove performance information to practitioners disseminating stove technology in the field.

Key words: Water boiling test; Improved cook stove; Efficiency; Performance

Introduction

It is estimated that around two-thirds of the populations of developing countries rely on biomass fuel (wood, dung and fibre residues) for cooking and heating, involving around three billion people (Anomymous, 1998). Improved cooking stove projects in the developing world have the potential to reduce deforestation, improve health, and slow climate change. To meet these requirements, stoves must be carefully designed through thorough testing and verification of performance. The systematic investigation of the heat transfer and combustion efficiency of stove design in the laboratory sheds light on what technologies work best and helps to ensure that stoves being disseminated are truly a significant improvement over traditional cooking methods

Utilizing the ICS to mitigate negative impacts of solid biomass consumption involves a dual challenge. First, there is a design problem: a technically appropriate and cost-effective stove must be developed. Second, there is the challenge of dissemination: in order to effect positive change, the stove must be introduced into people's kitchens and adopted into their daily cooking practices. The end-result of an intervention is as much a function of user preferences and behavior as the technical design of the ICS. The stove user, however, often goes unstudied in household energy interventions (Ezzati and Kammen, 2002).

A literature survey was conducted, and we found that many solid-fuel stoves have been tested for performance and emissions (Mumford *et al.*, 1987; Smith *et al.*, 1993; Ballard-Tremeer and Jawurek, 1996; Gupta *et al.*, 1998; Oanh *et al.*, 1999; Zhang and Smith, 1999). In most cases, reductions in fuel consumption resulting from improved stove dissemination have been based on WBT-style efficiency tests conducted under laboratory or highly-controlled field conditions. Hundreds of fuel-saving cookstove designs have been promoted worldwide (Still *et al.*, 2007). Most have undergone some type of lab testing, typically with a variant of a WBT, but in Bangladesh most of the ICS have not tested by this standard method.

WBT is a laboratory test that involves the investigation of the cooking stoves in a controlled environment in order to evaluate or reveal their technical performance. This method focuses on simulation of cooking practices by water boiling hence does not present the actual cooking conditions. WBT is very vital at the time of the design of the cook stoves (Rob *et al.*, 2007). Although WBTs were initially designed as laboratory tests, it is important to note that they can as well be carried out in the field particularly for in situ cook stoves or huge cook stoves that cannot be transported to the laboratory.

The process of testing involves three main stages i.e. (a) Cold Start (high power phase) - This stage involves raising the temperature of water from ambient temperature to boiling point from a cold start. This simulates rapid cooking tasks like making tea, boiling milk etc. (Rob *et al.*, 2007). (2) Hot Start

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(high power phase) - This stage involves raising the temperature of water from ambient temperature to boiling point when the stove is already hot and (3) Low power simmering phase - This phase involves maintaining the boiling water at simmering temperatures i.e. about 2-3 degrees below the boiling point of water. This simulates slow cooking tasks like cooking rice, beans or hard grains (Rob et. al., 2007). The key parameters that can be investigated by WBT include; thermal efficiency, combustion efficiency, fuel consumption, fuel burn rate and time to boil. These parameters measure the technical performance of stoves and vary from one stove to the other. Note that the tests must be carried under the same conditions in order to obtain meaningful results. Fig. 1 summarises the three main stages of WBT.

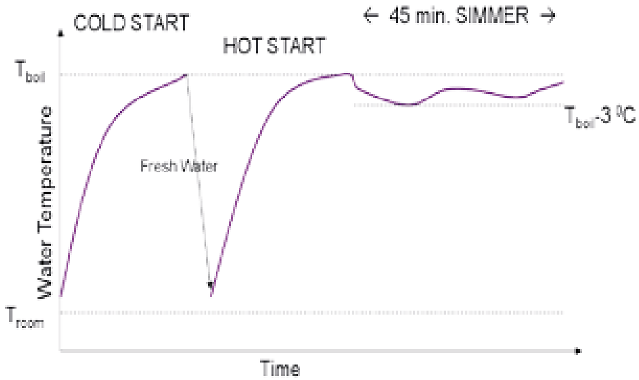

Fig. 1. WBT procedure

Stove performance testing can assist stove developers with both the design challenge and the dissemination challenge. Lab-based tests are vital during the design stage of the ICS. These inform designers about the effectiveness with which different stoves transfer the energy released from the combustion process into the cooking pot. In addition, lab testing allows designers to quickly explore the performance of different materials and assess variations in stove geometry. In contrast, field tests provide a kind of "reality check" for stove designers by documenting the performance of stoves in the hands of actual users in their own kitchens. This can be extremely useful, particularly in the early stages of stove dissemination.

Objective of this research was to test the ICS performance using lab-based water boiling tests (WBTs), which yield a number of performance indicators including time to boil water, specific fuel consumption, average fire power and energy efficiency when the stove is operated at both high and low power output. This paper describes the monitoring and evaluation of three ICS provided by GIZ, which were they disseminated throughout the Bangladesh and compare the result with the traditional stoves used in Bangladesh.

Materials and methods

Visual Inspection

The four cook stoves were first photographed (Fig. 2- 5) and visually inspected. The following attributes were measured during the visual inspection:

- Number of holes in grate
- Internal top diameters of the stove, ID1 and ID2
- Depth of the stove, h
- Dimensions and area of air inlet port, Inlet 1
- Dimensions and area of firewood feeding port, Inlet 2
- Air gap between cooking pot and stove

Fig. 2. Traditional single mouth underground stove used in Bangladesh which is made of clay and without grate.

Fig. 3. Single mouth half underground improved stove which is made of clay with grate.

Testing Location

The water boiling tests (WBT) were performed at the Institute of Fuel Research & Development (IFRD), BCSIR, Dhaka, Bangladesh over a 10 days period from 20 June 2011. All tests were conducted in an enclosed shed in ambient conditions (i.e. without climate controls).

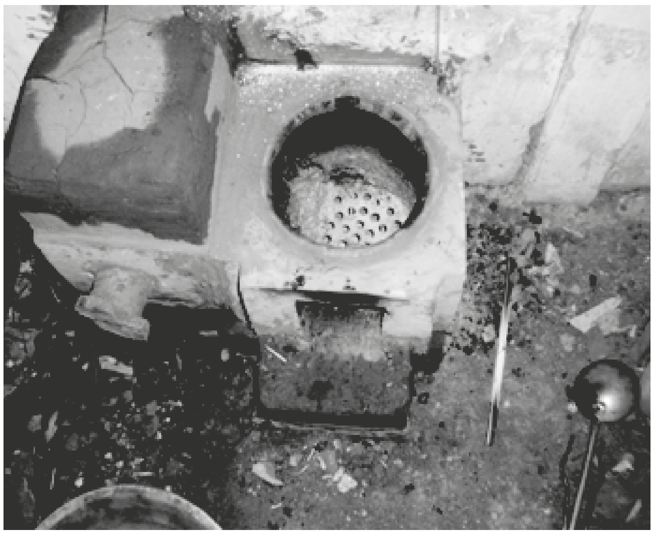

Fig. 4. Single mouth over ground improved stove which is made of concrete with grate and chimney.

Fig. 5. Double mouth over ground improved stove which is made of concrete with grate and chimney.

Testing Apparatus

The following equipments were used for the experiments:

a) Thermometer

b) Weigh scales, 6kg limit & 1g resolution

c) Digital timer

d) Round bottom cooking pots

e) Heat resistant mat for the weigh scales

f) Heat resistant gloves

g) Tray for hot wood

h) Measuring jug

i) Fire lighting material

j) Wooden fixture for holding thermocouple in the water

Fuels Tested

Stoves were tested in this study by using wood, cow dung ball and cow dung stick as fuel. For all of the experiments and the cow dung ball and cow dung stick was purchased from a single source. The wood was also procured from a single source.

The species and average moisture content of the woods is 14%. For this study, the wood was classified as average softwood, and the calorific heating value used was 20,814 kJ/kg, as suggested by Aprovecho (Anomymous, 2009).

Protocols

The thermal efficiency of a stove is usually defined as the ratio of heat transferred to the cooking medium to heat supplied by the fuel. Of various te sting methods the Water Boiling Test (WBT), version 3.0 was used to evaluate the stoves (Battacharya et. al., 2002; Battacharya et. al., 2000 and Kshirsagar, 2009). The tests consist of three phases:

1. Cold Start (high power): Using a cold stove and a cold pot, 3.0 L room temperature water was brought to a boil.

2. Hot Start (high power): Immediately following the cold start, the water is replaced with a new batch of 3.0 L of room temperature water which is brought to a boil.

3. Simmer (low power): Immediately following the hot start, the already boiled water is maintained at a simmer for 45 minutes. In this phase, the stove, pot and water remain hot from the second phase of the test.

These phases were used for simultaneous collection of data for thermal efficiency of the stoves. The round bottom, 15" diameter aluminum pot, purchased from local market, was used for all tests.

Analysis

For each metric, we report stove performance on the WBT both as a whole, averaged or summed over all three phases, as well as average performance solely on the simmer phase. Performance during simmering phase is particularly important. With that in mind, in addition to presentation of results from all phases of the WBT combined, we have isolated the results of the simmer phase, separate from the cold and hot start portions of the WBT. This report will enable readers may see how each stove performs specifically during the simmer phase as well as over the entire test.

The weight of water and fuel used are both weighed prior to, and immediately after the test period. This determines the fuel burnt and the water evaporated. Additionally the temperature is monitored from start to finish at minute intervals. This gives the change in temperature provided by the fuel and also a profile curve of the stoves heating performance.

Results and discussions

Visual Inspection

The study "Improved Biomass Cooking Stove for Household Use" (Anomymous, 1984) identified a number of factors that would affect the efficiency of a stove; the stoves tested in this study have approximate dimensions as per Table-I.

In the hot start boiling, in which room temperature water is placed on already heated stoves, all of the stoves required almost same time to boil the water from 14.1 min for traditional stove to 18.8 min for single mouth concrete stove, shown in Fig. 7. As expected, in that case the required time was much lower than the water boiling time when cold start.

Thermal Efficiency

Thermal efficiency is the "ratio of the work done by heating and evaporating water to the energy consumed by burning wood."

$$h_c = \frac{4.186 * (P_{ci}-P) * (T_{cf}-T_{ci}) + 2260 * (w_{cv})}{f_{cd} * LHV} \quad \text{-------(1)}$$

Here,

P_{ci} = Weight of Pot with water before test (g)

P = Dry weight of empty Pot (g)

T_{cf} = Water temperature after test (ºC)

T_{ci} = Water temperature before test (ºC)

w_{cv} = Water vaporized (g)

f_{cd} = Equivalent dry wood consumed (g)

LHV = Net calorific value (dry wood) (MJ/kg)

Table I. Approximate dimensions of significant factors of the stoves

Stove type	Depth (cm)	Dimension of stove (cm x cm)	Dimension fuel input mouth (cm x cm)	Dimension of exhaust gas outlet (cm x cm)
Traditional stove	41	24×25	15×17	-
Single mouth half underground clay stove	25	24×24	12×12	6×6
Single mouth concrete stove	22.5	22×22	12×13	6×6
Double mouth concrete stove	24	24×25 (1^{st} mouth) 22×22 (2^{nd} mouth)	12×15	12×12 (1^{st} to 2^{nd} mouth) 6×6 (2^{nd} mouth to exhaust)

Time to Boil

The traditional stove, single mouth concrete stove and double mouth concrete stove have needed almost equal time to boil the water when cold start e.g. 25.8 min, 23.7 min and 24 min respectively. But single mouth half underground improved stove made of clay have needed more time (31.8 min) to boil the water when cold start. Fig. 6 shows the average time to water boil from cold start.

In this calculation, the work done by heating water is determined by adding two quantities: (1) the product of the mass of water in the pot, (P_{cn}– P), the specific heat of water (4.186 J/g^{0}C), and the change in water temperature (T_{cv}– T_{cn}) and (2) the product of the amount of water evaporated from the pot and the latent heat of evaporation of water (2260 J/g). The denominator (bottom of the ratio) is determined by taking the product of the dry-wood equivalent consumed during this phase of the test and the LHV.

$$h_s = \frac{4.186 * (P_{hi}-P) * (T_{hf}-T_{hi}) + 2260 * (w_{hv})}{f_{hd} * LHV} \quad \text{-------(2)}$$

$$h_s = \frac{4.186 * (P_{si}-P) * (T_{sf}-T_{si}) + 2260 * (w_{sv})}{f_{sd} * LHV} \quad \text{-------(3)}$$

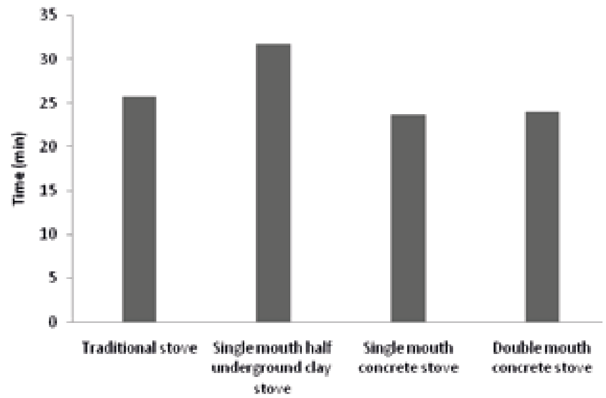

Fig. 6. Average time to water boil from cold start

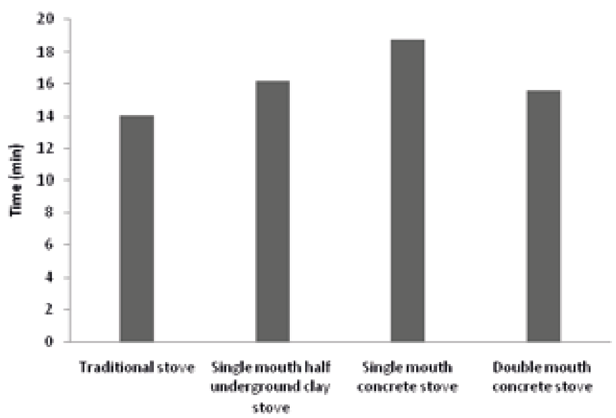

Fig. 7. Average time to water boil from hot start

The symbol hc, hh and hs are the thermal efficiency of cold start, hot start and simmering phase respectively. All of the symbols with subscripts c, h and s indicate these three phases accordingly. The detail about these calculations for determining thermal efficiency can be found in the WBT protocol (Anomymous, 2009).

Fig.8. show the thermal efficiency of each of the stoves for hot start, cold start and simmer phase as well as the average efficiency of over all phases of the WBT (Fig. 9). Average thermal efficiency results of double mouth concrete stove was better than the any other stoves and the efficiency was 15%. Other three stoves including traditional stoves the

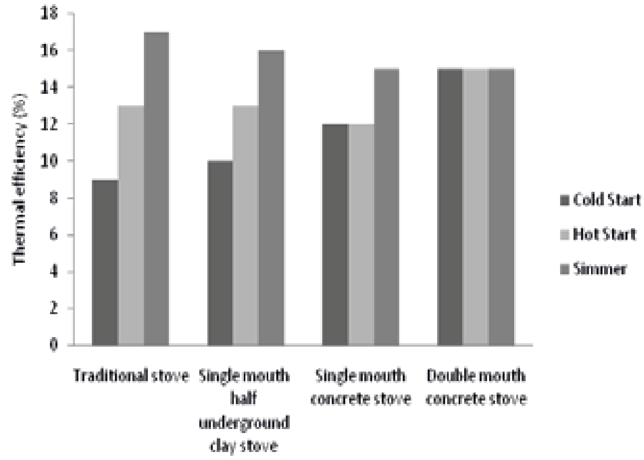

Fig. 8. Average thermal efficiency for cold start, hot start and simmer phase

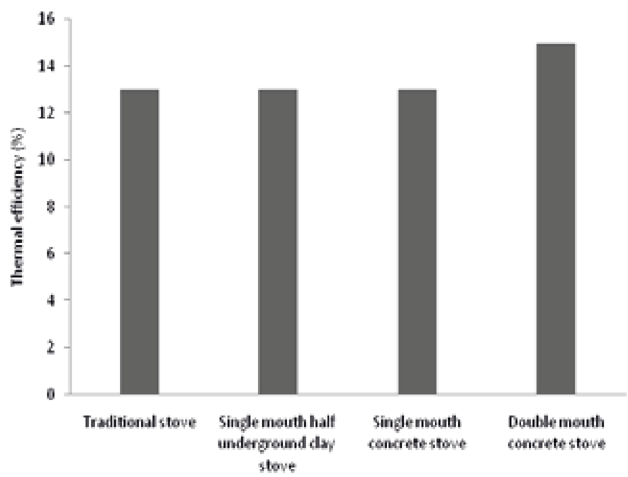

Fig. 9. Average thermal efficiency for entire WBT

efficiency was same, 13%. All stoves including the traditional stove, showed higher efficiency during the simmer phase than the hot or cold start phases. We note that the variation could come from a number of factors, only some of which are related to stove design and actual performance and that a larger sample size would be useful for future analysis.

Specific Fuel Consumption

Specific fuel consumption is defined in the 2007 WBT as "the fuel wood required to produce a unit output" whether the output is boiled water. In the case of cold start high power WBT, it is a measure of the amount of wood required to produce one liter (or kilogram) of boiling water starting with cold stove. Our results show the temperature corrected specific fuel consumption, which adjusts for differences in initial water temperatures.

From Fig.10 it can be clearly seen that, the simmer phase accounted for a large portion of the fuel consumed for each stove. Specific fuel consumption results for the entire WBT, it is clearly seen that double mouth concrete stove consumed less fuel than any other stove (223.2 g/L). But single mouth clay stove and single mouth concrete stove consumed more fuel (280.4 g/L and 271.1 g/L respectively) than the traditional stove (239.7 g/L). Fig. 11 shows that the specific fuel consumption for entire WBT.

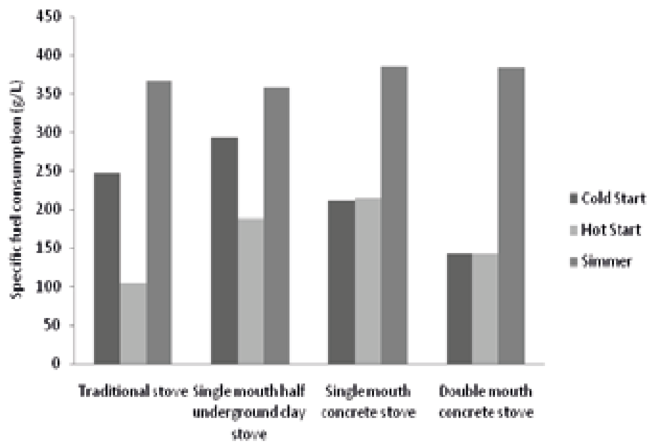

Fig. 10. Specific fuel consumption of the stoves for cold start, hot start and simmer phase

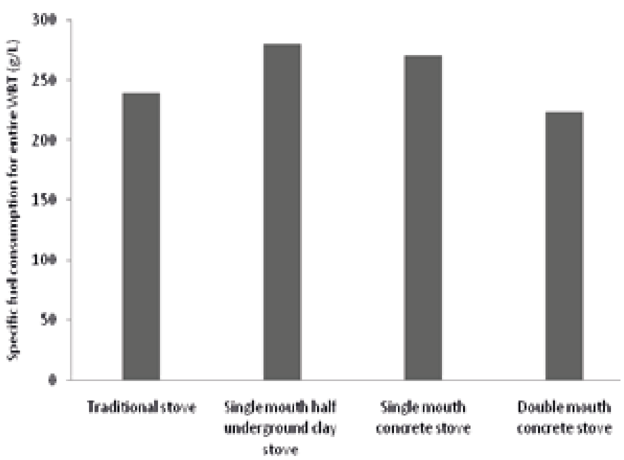

Fig. 11. Specific fuel consumption for entire WBT

Average Firepower

The average firepower of the stove (in Watts), through both the cold start (i.e. high power) and simmer (i.e. low power) phases of the water boiling test, is calculated as follows:

$$P = \frac{H_v * m_f}{t}$$

Where, P is the average firepower of the stove (Watt), Hv is the calorific heating value of fuel used (kJ/kg), mf is the mass of fuel used (g) and t is the time taken to complete the test (45min = 2700s)

When cold start the traditional stove had the highest average firepower (8603 watts) but in the hot start and simmer phase double mouth concrete stove had the highest average firepower (12825 watts and 5639 watts respectively) than the any other stoves. Fig. 12 shows the average firepower of the stoves for cold start, hot start and simmer phase.

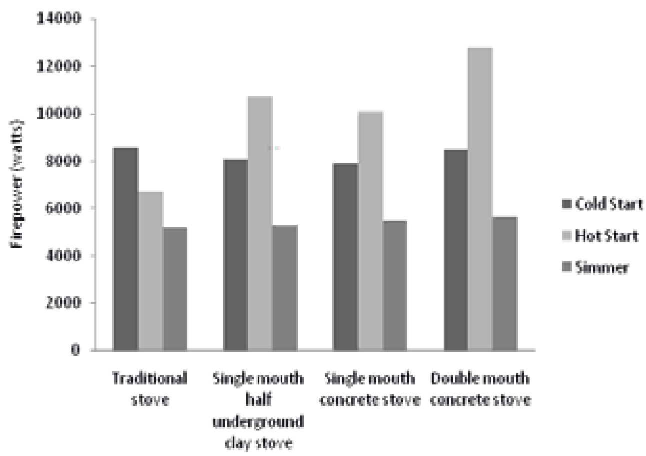

Fig.12. Average firepower of the stoves for cold start, hot start and simmer phase

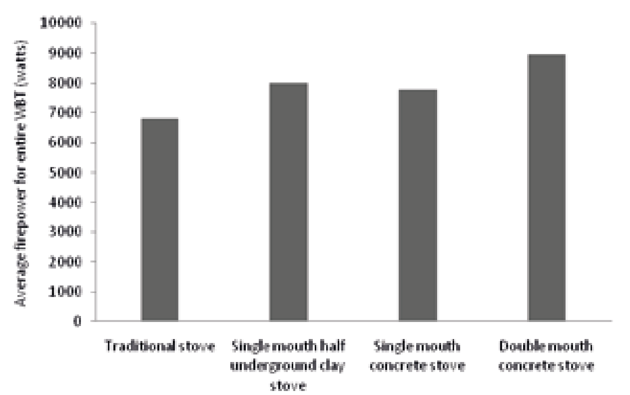

Fig. 13. Average firepower for entire WBT

For the entire WBT, double mouth concrete stove had the highest average firepower (8985 watts) than the any other stoves. It can be clearly seen that from Fig.13, traditional stove had the lowest average firepower for entire WBT (6824 watts) and single mouth clay stove and single mouth concrete stoves average fire power were 8031 watts and 7815 watts respectively.

General Discussion of WBT Results

Thermal Efficiency

- The average stove is said to retain moisture during its manufacture and should be fired for a period of time (e.g. 30 min) before first use to dry it out. One would expect that the efficiency of the stove would be poor during the first test and improve after subsequent tests. This hypothesis is generally borne out in the testing; however some stoves have consistent efficiency throughout all the tests.
- The efficiencies calculated in this study cannot be compared to stoves tested in other studies due to the sheer number of variables in testing, e.g. testing methods, types of fuel used, ambient conditions, etc.

Therefore the efficiency values cannot be regarded as absolute values and can only be used for relative comparisons between like stoves.

Sources of Experimental Error

- Different testers possessed different skill levels for creating and maintaining fires (especially for the firewood tests). While this was controlled as much as possible, there were some variations resulting from the ability of testing staff (e.g. the local staff was generally more adept at maintaining strong wood fires). This suggests that the skill of the cook can be as important a factor as the efficiency of the stove.
- The orientation/layout and burning capability of the fuel in the stove was difficult to control and resulted in some fires burning well, while other fires merely smoldering. The effects of these errors were mitigated by repeated testing and discarding results that were incongruous with other tests.
- The firewood came from a single source, but the wood did not appear to be from a homogenous species. The level of dryness of the wood also varied among the sample.
- There was significant build-up of carbon residue on the surface of the pots (especially after wood stove tests), which may have affected the thermal efficiency of the pots. The bottom surface of each pot was scraped before a wood stove test, but the carbon build-up was unavoidable.

Conclusion

The WBT is considered as one of the most reliable test for the performances of cook stove. Double mouth concrete stove is clearly the best stove based on all testing indicators. It has the highest average efficiency, lowest specific fuel consumption and highest firepower. But for the entire WBT, specific fuel consumption of single mouth clay stove and single mouth concrete stove are more than the traditional stove. Efficiency of single mouth concrete stove is same as the single mouth clay stove. It is expected that double mouth concrete stove and double mouth clay stove will have the same efficiency. Results show that traditional stove has the lowest average firepower for entire WBT. In addition to these it has been found that during testing period development of cracking was not observed. But after long use of the concrete stove there is a possibility to development of cracking. This problem can be solved by putting a layer of clay on the internal surface of the stove.

Recommendation for future work

The following recommendations for future work on cook stove testing are proposed:

- Use an insulated and air-conditioned room for the testing, in order to control ambient temperature and humidity. An extraction fan would also be an advantage to prevent smoke inhalation.
- Employ only one tester to minimize variations in tester skill. The recommended schedule is 2 WBTs per day.
- Other than wood e.g. cow dung ball and cow dung stick is not suitable for stove testing.
- Explore cooking techniques and other mitigation factors that will take advantage of its high power and thermal efficiency characteristics, while still maintaining high fuel efficiency.
- Emission of smoke (CO2, CO etc) from the stove should be determined.

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Received: 27 November 2013; Revised:10 June 2014; Accepted: 25 August 2014.