Design and Performance Evaluation of Rocket Stove for Cleaner Cooking in Rural Ethiopia

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Original article

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Abstract

Background:

Many rural households in Ethiopia use traditional three-stone stove which has low energy efficiency and incurs indoor air pollution. Despite the fact that improved cook stoves design variability was seen between producers appears, they have received little or no promotion work to improvements over open fire stoves. The aim of this research work is manufacturing and experimentally testing of rocket stove to make sure that the new design provides a major improvement within the prevailing cooking practices.

Method:

The rocket stove was developed as per the Aprovecho Research Center (USA) design principle the article focused on investigating the thermal performance, the specific fuel and emission reduction potential of rocket stove as compared to the three-stone stove so as to confirm the duplicability. Water boiling test were conducted to investigate the performance of developed rocket stove and emission characteristics were investigated using portable Indoor Air Pollution (IAP) monitoring device. The parameters and protocols were adjusted as per the Aprovecho design principles.

Results:

The result revealed that the rocket stove has 29% thermal efficiency, 43% reduction in specific fuel consumption, 42% CO and 81% $PM_{2.5}$ emission reduction as compared to the well-known utilized traditional three-stone stove in Ethiopia. The experiment revealed that, the rocket stove average emission is 1.8 $\mu g/m^3$ CO and 10 $\mu g/m^3$ $PM_{2.5}$ respectively. The emissions characteristic of our stove satisfies the WHO indoor air quality standard.

Conclusion:

It can be concluded that the prototype rocket stove has a substantial improvement over the three-stone stove with regards to thermal efficiency, CO and $PM_{2.5}$ emissions. Furthermore, the stove can be manufactured locally within required thermal efficiency and emission levels. Therefore, shifting to rocket stoves could reduce pressure on forests and mitigate indoor pollutants emission.

1. Introduction

Wood is an important source of energy that has been used for eras for cooking, boiling water, lighting and heating [1]. Today, an estimated 2.8 billion do not have access to clean cooking facilities. A third of the world's population, 2.5 billion people rely on the traditional use of solid biomass to cook their meals[2]. In sub-Saharan Africa, more than 90% of the population relies on firewood and charcoal derived from wood as a primary source of domestic energy [2]. Like many other sub-Saharan African countries, Ethiopia's energy supply is heavily dependent on biomass which accounts for above 95% of the energy use [3]. But burning wood fuel traditional way has been criticized for its negative impacts on the environment and indoor health which has resulted in policies and campaigns to discourage its use [4]. According to [5] traditional stoves are still the most prevalent way of cooking in the developing countries regardless of their inefficiency and risks associated to human health and the environment. As [6] reported that dominant cooking practice is a three-stone open fire system in Sub-Saharan African countries.

The current inefficient cooking employed in the developing world have negative health impacts. Poor combustion efficiency in cooking stoves converts wood fuel into particulate matter, carbon monoxide and other gases that are responsible for health problems associated with indoor air pollution [7]. Such cooking stoves are not efficient in energy use, and they also bring about environmental impacts like decline of forest and associated emission of greenhouse gasses such as carbon dioxide [8]. In Ethiopia traditional stove are commonly used in urban and semi urban settings. The inefficient fuel combustion in traditional stoves release gaseous products with a higher global warming potential than carbon dioxide, such as carbon monoxide[9].

The most serious consequence of burning biomass in the home is the risk to expose the cooks to respiratory and lung diseases. According to the World Health Organization, 1.6 million premature deaths occur each year as a result of indoor smoke inhalation, and more than half of these deaths occur among children under five years of age. As a result of population growth, this problem will continue to worsen [10]. Thus, there is an urgent requisite to emphasis on clean cooking energy issues.

In developing countries like Ethiopia, whose energy supply is heavily reliant on biomass fuels, technical advances in energy efficiency are critical. To deal with this problem, many are being made by the government and non-government organizations since the beginning of 1990s. For instance, the government of Ethiopia is trying to extend the supply of fuel saving improved cook stove technologies so as to reduce pressure on forests and therefore the adverse impact of indoor pollution [11]. In addition, non-governmental organizations mainly GIZ, are engaged on afforestation programs and dissemination of more efficient improved cook stove technologies [12]. the development of ‘Mirt’ Injera stove, Gonzie’ biomass injera and pot stove, ‘Lakech’ charcoal stove, Merchayie charcoal Stove, tikikil stove and Institutional Rocket Stove currently are a number of the results of those efforts within the country [13].

Among the above mentioned efficient improved cook stoves, Tikikil stove is an example of the common “rocket elbow” design which consists of a ceramic liner and a metal cladding constructed of galvanized steel. Despite the very fact that the Tikikile is standard design, an outsized amount of variability was seen between producers appears and have received little or no promotion work thus far outside of Addis Ababa [13]. Therefore, the stove needs cautious performance and user favorite studies prior preamble of model to make sure that the new design provides a major improvement within the prevailing cooking practices. To our knowledge, comprehensively studies were shown on performance of injra baking and charcoal stoves. Hence, the aim of the study is design improvement and performance testing of wood fuel rocket stove (tikikil) for cleaner cooking in rural segments of Ethiopia. To these ends, the main metrics resulting from the experimental tests are thermal efficiency, specific fuel consumption and emissions reduction to complete the task of producing a boiled and simmered liter of water.

2. Material And Methods

- **Materials**

Mild steel sheet metals and Red ash are used for manufacturing a stove. The dimension of the stove is sized for a household of average family size in Ethiopia.

A bark free eucalyptus wood (Eucalyptus globules) was used as fuel source for performance evaluation of the locally fabricated cook stove in Bahir Dar, Ethiopia. The fuel wood prepared was dried in an oven at 105°C and stored in an airtight container. The eucalyptus fuel wood is a locally dominant wood species typically used for cooking and heating in all seasons. The proximate analysis and calorific value of the eucalyptus wood sample were taken from published articles and the values are summarized in Table 1.

Table 1: Physical and thermal characteristics of wood (Eucalyptus)

Properties	MC (Wt. %)	VM (Wt. %)	Ash (Wt. %)	FC wt.%	Heating value (KJ/kg)	Reference
Value	5.64	80.81	0.54	13.4	18.64	[11]

The Indoor Air Pollution (IAP meter 5000) monitoring device, equipped with electrochemical cell and red laser scattering photometer, was used for measuring the CO and particulate matter ($PM_{2.5}$) emission characteristics of the fabricated stove and the three stones stove under water boiling test. Average emission concentrations, of the rocket stove and the three stones stove, during the test were recorded and compared according to indoor air quality standard of world health organization.

A suitable weight gauge of ±0.01kg precision was used to measure the wood fuel consumption of the stove and charcoal remaining during the test. In addition, k-type thermocouples were used to monitor the temperature of the water during the water boiling test.

2.2. Fabrication of stove

The cook stove in this study was designed based on the design principle for wood burning cook stoves, developed at the Aprovecho Research Center [12]. The design guide and critical stove dimensions were dictated by the size and geometry of the primary cook pot to be used during stove operation. A single pot, rocket stove was then manufactured for laboratory based performance testing at Bahir Dar Institute of Technology, Bahir Dar University; Bahir Dar, Ethiopia. The stove consists following features: vertical L-shaped insulated cylindrical combustion chamber, rectangular fuel magazine (fuel shelf), cylindrical pot skirt and metal pot rest. The components were sized according to [12].

The vertical L-shaped combustion chamber which forms an internal chimney was designed for 250mm cooking pot. The area of the combustion chamber, which will be continued throughout the stove, is determined using Equation 2.1:

[Please see the supplementary files section to view the equation.] ………………………………… *(2.1)*

[Please see the supplementary files section to view the equation.] …………………………………….. (2.2)

[Please see the supplementary files section to view the equation.] ……………………………………. (2.3)

[Please see the supplementary files section to view the equation.] ……………………………………… (2.4)

[Please see the supplementary files section to view the equation.] ……………………………………. (2.5)

Rectangular fuel magazine was chosen in this design for the easy of manufacturing and supplying excess air for complete combustion fuel during cooking period.

2.3. Stove performance testing

The performance indicators (time requier to bring water boiled, Thermal efficiency, specific fuel consumption and emission reduction of the rocket stove in comparison to traditional three-stone stove were assessed using the water boiling test. The procedures outlined in the water boiling point test (WBT version 4.1.2) [13] were used to evaluate performance of the stove for recommended small standard pots with 2.5 liter capacity.   The test evaluates a stove during three separate phases of operation: Cold start (high power), hot start (high power) and simmering test. The thermal efficiency, a measure of the fraction of heat produced by the fuel that made it directly to the water in the pot is calculated by [14] and using the empirical equation 2.6 .

[Please see the supplementary files section to view the equation.] …………………….. (2.6)

Specific fuel consumption measures the quantity of fuel required to boil (or simmer) 1 liter of water. It's calculated by the equivalent dry fuel used minus the energy within the remaining charcoal, divided by the liters of water remaining at the completion of the test. The specific fuel consumption, Sc to vaporize amount of water were calculated as from equation 2.7

[Please see the supplementary files section to view the equation.] ………………… (2.7)

Environmental performances of the stoves were measured in conjunction with thermal performance testing. The concentrations of CO and $PM_{2.5}$ in each WBT test were measured using portable Indoor Air Pollution (IAP) monitoring device. The instrument was fixed 1.5 m above and 1 m to the side of the cooking pot and set to record. The CO concentration and $PM_{2.5}$ level were measured at 22 second intervals during cooking period.

A specific fuel consumption and emission reduction potential of stove was computed by comparing with the corresponding values of the traditional three-stone stove using equation 2.8.

[Please see the supplementary files section to view the equation.] ……. (2.8)

3. Results

- **Stove prototype and dimensions**

The locally fabricated stove consists of the following features: vertical L-shaped insulated combustion chamber, rectangular fuel magazine (fuel shelf), and removable cylindrical metal pot skirt and pot rest on the skirt. Figure 3.1 shows the most relevant geometric features for our study and Figure 3.2 gives the main dimensions of the components. The height of combustion chamber, the internal diameter of the combustion chamber, the fuel magazine height, fuel magazine width, Pot skirt diameter, Pot skirt height, pot rest height (gap between bottom of the pot and top of combustion chamber), Insulation thickness and The total height of the cook stove are: H_{comb}= 290 mm, D_{comb} = 130 mm, $H_{fuel\ magazine}$=120 mm, $W_{fuel\ magazine}$ =128 mm, $D_{pot\ skirt}$ = 330 mm, $G_{pot\ rest}$ 32.88 mm, $H_{pot\ skirt}$ = 90 mm, thickness of insulation = 70mm and H_{stove}= 440 mm respectively.

- **Performance test result**

3.2.1 Time required to boiling water

In WBT experiment, water was heated to boiling point. The local boiling point of water was recorded 95.5^0C. The time required for bringing water to a boil from a cold start; bringing water to a boil when the stove is hot; and, maintaining the water at simmering temperatures in triplicate runs of tests are presented in figure 3.3.

As shown in figure 3.3, the rocket stove took 4, 3 and 7 minutes to bring water to boil point during cold start, hot start and simmer test respectively. However, the three-stone stove took 8, 6 and 11 minutes. In all tests the rocket stove took shortest time regardless of fuel type.

3.2.2. Thermal efficiency

Thermal efficiencies of two stoves are presented as a means of comparison in figure 3.2.
The test was performed three times to provide a simple benchmark for evaluation.

As seen in the figure 3.4, rocket stove and three stones stoves have (20.45%, 13.5%), (32.24%, 14.5 %) and (34.43 %, 16.5 %) thermal efficiencies during cold start, hot start and simmering are respectively. It was found that, the designed stove had a mean thermal efficiency of 29%. This means that 29% of the total energy produced by the fuel is used to boil water in the pot. While three-stone stove has average thermal efficiency of 14.83%.

3.2.3 Specific fuel consumption

The specific fuel consumption of rocket stove and three stone stove to complete the water boiling test was obtained 757g and 1333g per liter of water boiled. From this, the fabricated stove shows 43% reduction in specific fuel consumption.

3.2.4 Stove emission reduction

Plots of CO and $PM_{2.5}$ of rocket stove and three-stone stoves are shown in figure 3.4, figure 3.5 respectively.

As shown in figure 3.5, the average CO and $PM_{2.5}$ was 1.8 ppm and 10μg/m^3 respectively. The highest (10.7ppm, 196μg/m^3) and lowest (1.4ppm, 31μg/m^3) 15-minutes concentration of CO and $PM_{2.5}$ pollutant was recorded over complete runs of the water boiling testing of the stove.

Figure 3.6 presented emission of three-stone fire in similar manner of the emission test of the rocket stove, the average CO and $PM_{2.5}$ was 3.1 ppm and 52μg/m^3. The highest (16.8ppm, 65μg/m^3) and lowest (1.2ppm, 70μg/m^3) 15-minutes concentration of CO and $PM_{2.5}$ pollutant was recorded over complete runs of the water boiling testing of the stove.

As comparison the average pollutant emissions of the rocket stove (RS) and traditional three stone (TTS) are shown in figure 3.7.

The rocket stove shows 42 and 81 percent reduction in CO and $PM_{2.5}$ emission as compared to three-stone stove

4. Discussion

As shown in Fig. 3.1 above, the design of stove takes account a pot skirt. The use of a pot skirt can reduce fuel use and emissions by 25–30% [15]. The cylindrical metal pot skirt on the top of the stove force the hot combustion gases close to the sides of the saucepan. The feature improves stove efficiency and pollutant emission through better combustion and heat transfer to the pot [15].

The stove height is one design parameter that can be adjusted to improve the thermal efficiency and is very significant for proper distribution of heat and flow of volatile matter towards utensils kept at the end of height. Studies [16] shows the effects of geometric aspects of rocket elbow for 500, 420 and 340 mm chimney. A 340 mm chimney height shows even distribution and effective heat transferred to the pot. However, formation of turbulence and uneven distribution of heat under pot was observed for the rest of chimney heights [16]. With this regard, the designed rocket stove dimension internal chimney height (290 mm) was reasonably good indication of improved thermal performance of volatiles at the end portion of chimney height.

The GTZ-Uganda shielded fire stove design guide suggests a stove body and internal combustion chamber height 2.5 times the height of the fuel inlet. Studies by [17] in evaluation of rocket stove operation height variation observed an increasing trend in thermal efficiency with a reduction in stove height. Pot-rests incorporated in this design holds cooking vessel in its position while create a channel below the pot and the chimney. Pot-rest ensure a complete combustion of the carbon monoxide by creating strong convection air flow to force the fast moving gases to punch through a boundary layer of still air that which create more turbulence within the chamber insuring a more efficient combustion. Combustion is then improved and less dangerous smokes emitted when pot-rest is made [18].

Time saving for cooking were analyzed based on the frequency cooking practice in most rural households. The trends in rural households, cooks are held three times in a day. The finding in this work shows that the use of rocket stove could save 12 minutes cooking time per day where cooking techniques involve water evaporation as an essential part of the cooking process as compared to traditional three stone stove. Similar studies in Ethiopia, also reported that improved cook stoves such as Mirchaye and Lakech stove can save 13–17 minutes cooking time per day when compared to traditional metal stove [19]. In Uganda, similar studies found that the average cooking time per household was reduced by 27 min per day when using the Rocket Lorena stove [20]

The thermal performance of the designed stove comparisons were made with locally existing stoves such as the Lorena stove, brick stove, Enviroft, supersaver premium stove, molded 1-pot stove, Kenya ceramic jiko stove, metal stove, trench fire, and the traditional 3-stone stove. Previous studies [21] show that the abovementioned stoves had thermal efficiency values of 14%, 17%, 35.7%, 16%, 24.5%, 21%, 13%, and 9%, respectively. Author [22] reported that thermal efficiency of portable household cook stove made of galvanized sheet metal with a ceramic liner rocket stove (Tikikil stove)is around 28%. Studies by [23] has also reported rocket stove (*Tikikil* stove) made from a combination of clay and metal has average thermal efficiency 33.5% during cooking food in pots or small frying pans. With a thermal efficiency of 29%, the designed prototype stove achieves tier 2 in the IWA tiers of performance [21] and the designed rocket stove has a substantial improvement over the baseline traditional 3-stone stove. This is due to the fact that the traditional stove fire is an open air system where most of the heat energy dissipates to surrounding air during cooking. Only about 8–12% of the energy content is obtained for cooking [24]. Previous studies [25] reports that three stone stove has average thermal efficiency 14.3%. Studies in few Asia countries shown traditional biomass-fired cooking stoves have low energy efficiency, typically in the range of 5–20% [24]. Past studies in Ethiopia also shown efficiencies of three-stone stoves have reported efficiencies of 7–8% [23] with other comparative studies reporting higher thermal efficiencies for the same type of stove ranging from approximately 14% [25] to 18% [26] and a 10% value provided as the clean development management default [3].

The SFC reduction in the present study was in the range (EnDev Ethiopia, 2015) report where rocket stove saves up to 50% of fuel compared to the three-stone open fire and for Ceramic Jiko ICS in Kenya which was 20–50%. According to [27], ICS can save up to 25% over traditional stove. In the other previous studies [15], rocket-type stoves can reduce fuel use by 33% on average in comparison to the three-stone fire. Studies in China, Guatemala, Gambia found that adoption of ICS reduced fuel wood consumption and wood collection time by 40.1, 39% and 40%%, respectively [28], [29], [19]. Thus, the present results have implications concerning forest degradation since the use of ICS can reduce pressure on forests.

The environmental performance the stove also compared with WHO indoor air quality standards and traditional open fire system. According to the World Health Organization, the acceptable amount of carbon monoxide during 1 hour of exposure is 30 ppm [30]. The concentration monitored during water boiling test of the rocket stove reached a maximum of 10.7 ppm. The amount of soot or particulate matter ($PM_{2.5}$) existing in a kitchen has an impact on the health of people in the room. The maximum recorded $PM_{2.5}$ concentration during the test session with the present rocket stove design was 196 μg/m^3 (Fig. 3.5). This value is well below the WHO standards that recommend concentrations below 10,000 μg/m^3 for annual exposure and 25,000 μg/m^3 during 24 hours exposure [30]. Conferring to [15], rocket-type stoves can reduce CO emissions by 75%, and PM emissions by 46% on average in comparison to the three-stone fire. For instance, in Ethiopia [19] found that Merchaye stove reduced emission of CO and $PM_{2.5}$ by 28 and 27% respectively in comparison to a traditional charcoal stove while Lakech stove reduced emission of CO and $PM_{2.5}$ by 15 and 13%, respectively. Similar studies in Mexico [31] asserted that ICSs reduced particulate matter (PM) by 74% and carbon monoxide CO concentrations by 78%. In the mid-hill region of Nepal, indoor concentrations of $PM_{2.5}$ and CO were found to be reduced by 63.2% and 60.0%, respectively, after one year of using the improved stove [32]. The adoption of ICS has significantly contributed to improvements in living conditions through wood savings, and reducing indoor air pollution [33].

The resent finding complies with other findings in CO and $PM_{2.5}$ emission reduction in which the use of this improved cooking stoves may also reduce greenhouse gas and particle emissions. The results of this study show that shifting from traditional open fire stoves to rocket stove could mitigate CO and $PM_{2.5}$ emissions

5. Conclusion

The rocket cooking stove was designed and fabricated using locally available materials including red ash, mild steel, and cement. Results from this study showed the cook stove has improved fuel efficiency and lower pollutant emissions compared with the traditional three-stone fire. Based on the water boiling test, excellent fuel use reduction and saving in cooking time per day is gained under water evaporation as an essential part of the cooking process. Significant improvement in thermal efficiency and emission reduction was achieved over the benchmark open fire stove. Based on comparisons with performance standards and properties of the conventional stoves, the fabricated rocket stove has a substantial technological improvement and can thus lessen the pressure on forestry resources and emission. But, additional studies including carbon and particulate matter (PM) emissions are suggested for forthcoming design improvements to suit public health standards. Studies on use of other forms of fuel such as briquettes and wood chippings could as well be conducted to establish fuel alternatives to charcoal.

Declarations

Ethics approval and consent to participate: - Not applicable' for that section

Consent for publication: - Not applicable' for that section

Availability of data and materials:-The authors are not willing to expose the available data as the research work is still on progress. Anybody who wants to get the data can contact us after the completion of the research work.

Competing interests: - Author declare no conflict of interest in this paper.

Funding: - The author has no any funding source to accomplish the work.

Author contribution: - The author has full engagement and contribution in manufacturing, experimental testing and manuscript writing. The reported data from this cook stove will contribute for farther improvements on design and give insight information to audience

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Figures

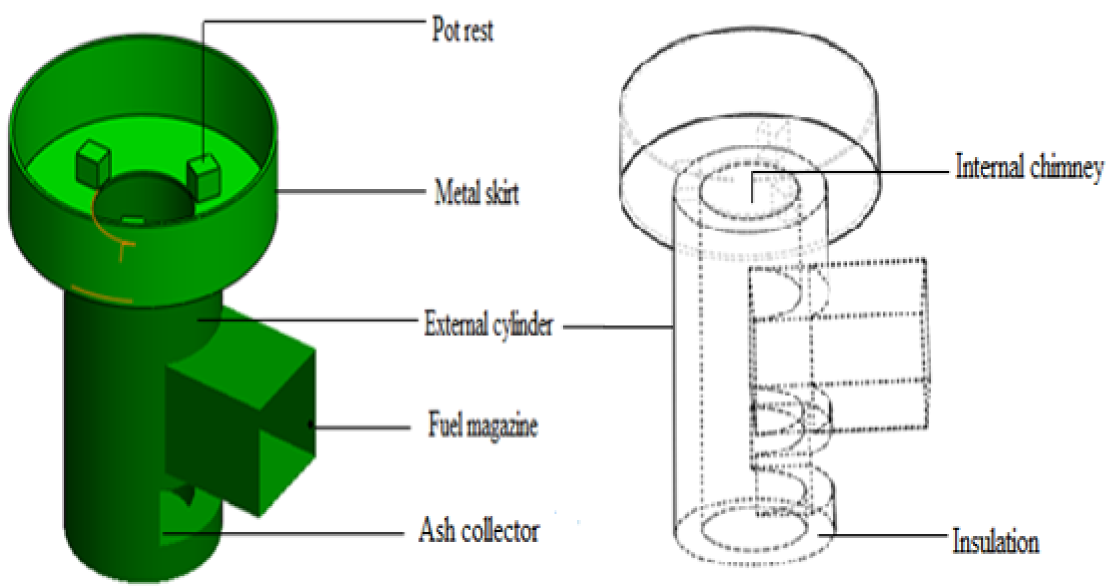
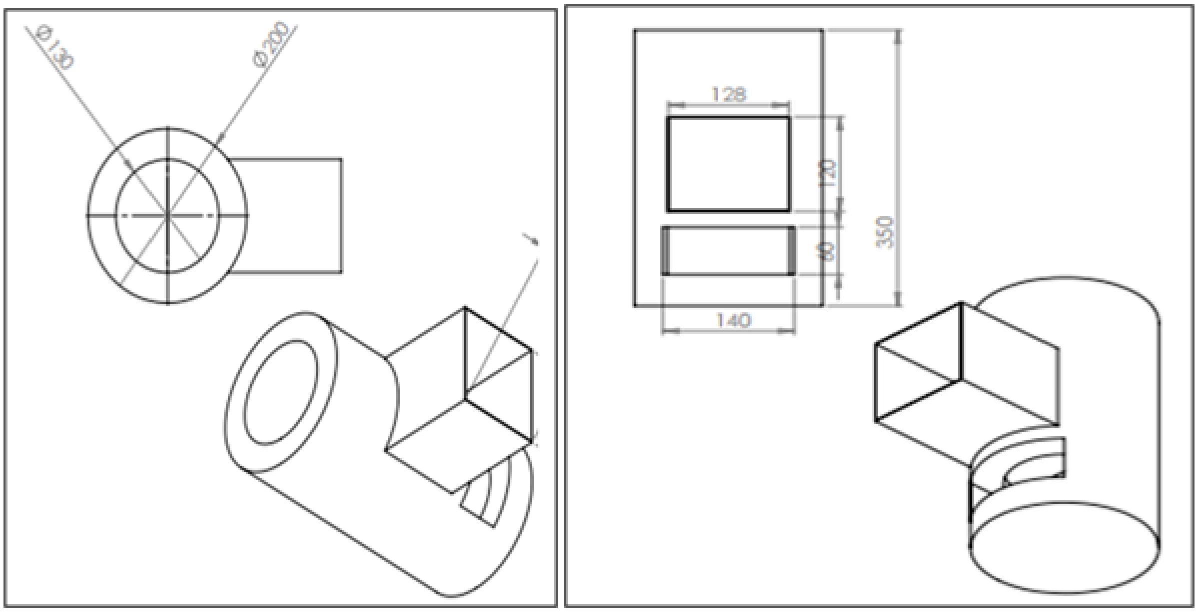


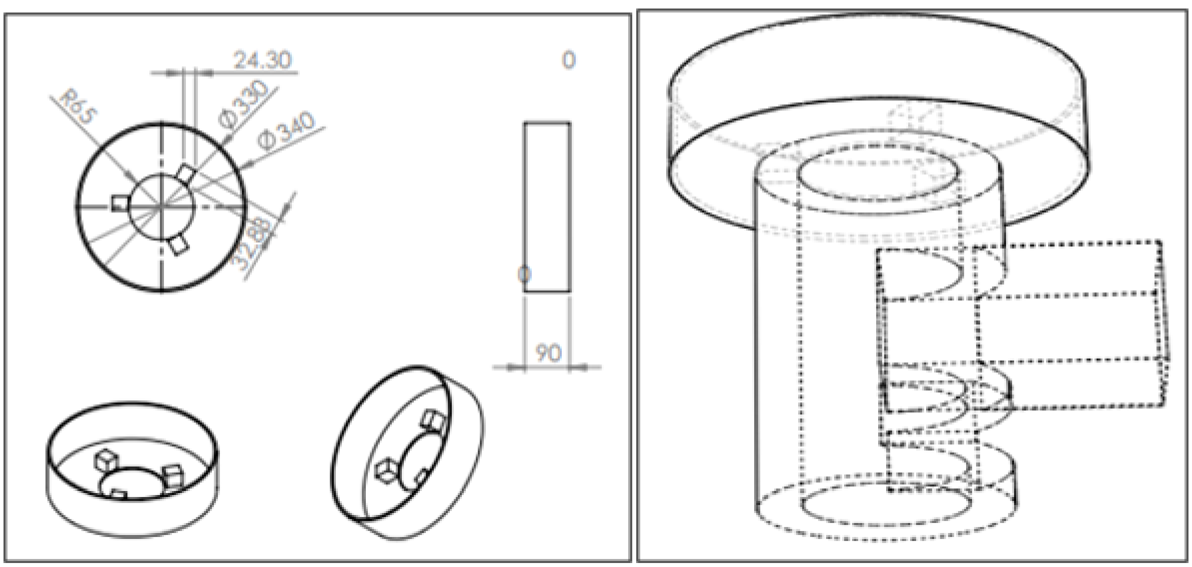
Figure 1

Prototype and component description of stove



a) Internal and external cylinder

b) fuel magazine and air inlet



c) Pot skirt and pot rest

d) Assembled stove

Figure 2

Dimensions of the stove components

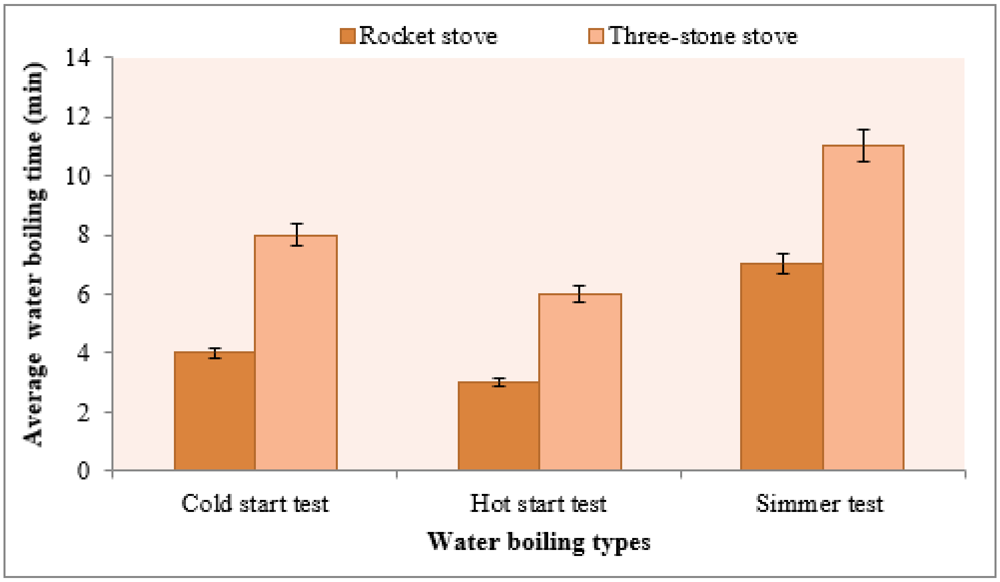


Figure 3

Average water boiling time (min)

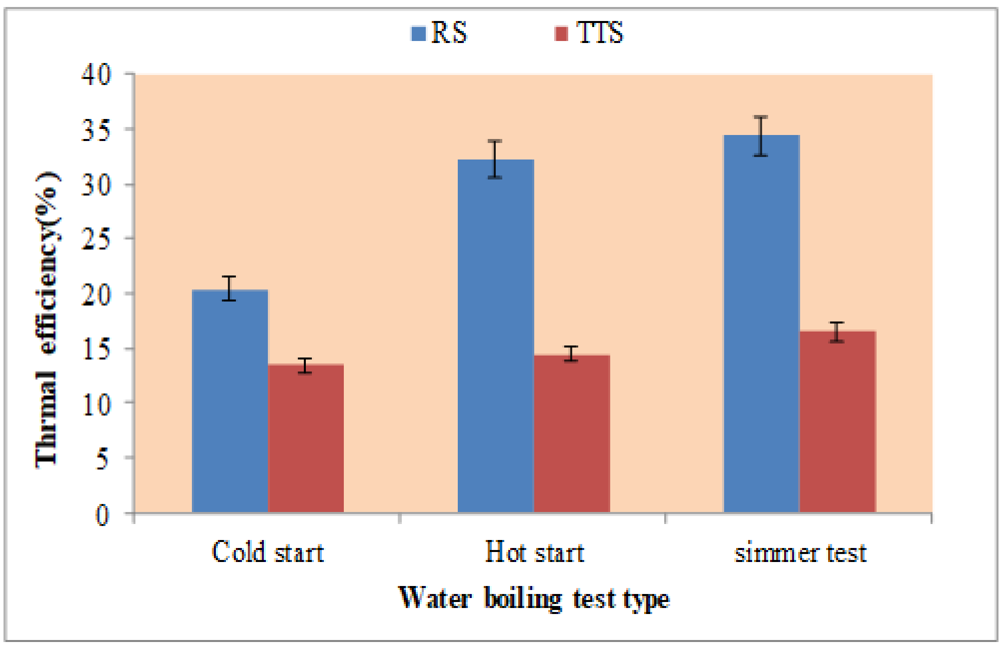


Figure 4

Thermal performance test

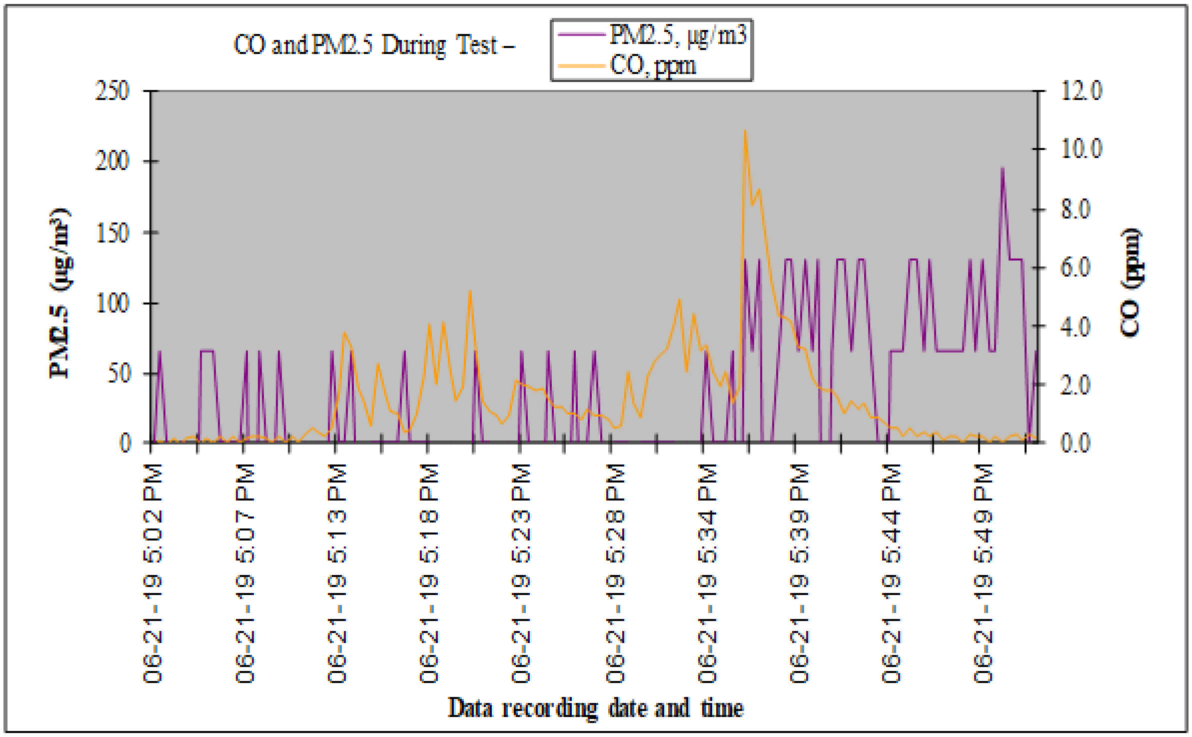


Figure 5

Emission test result of rocket stove

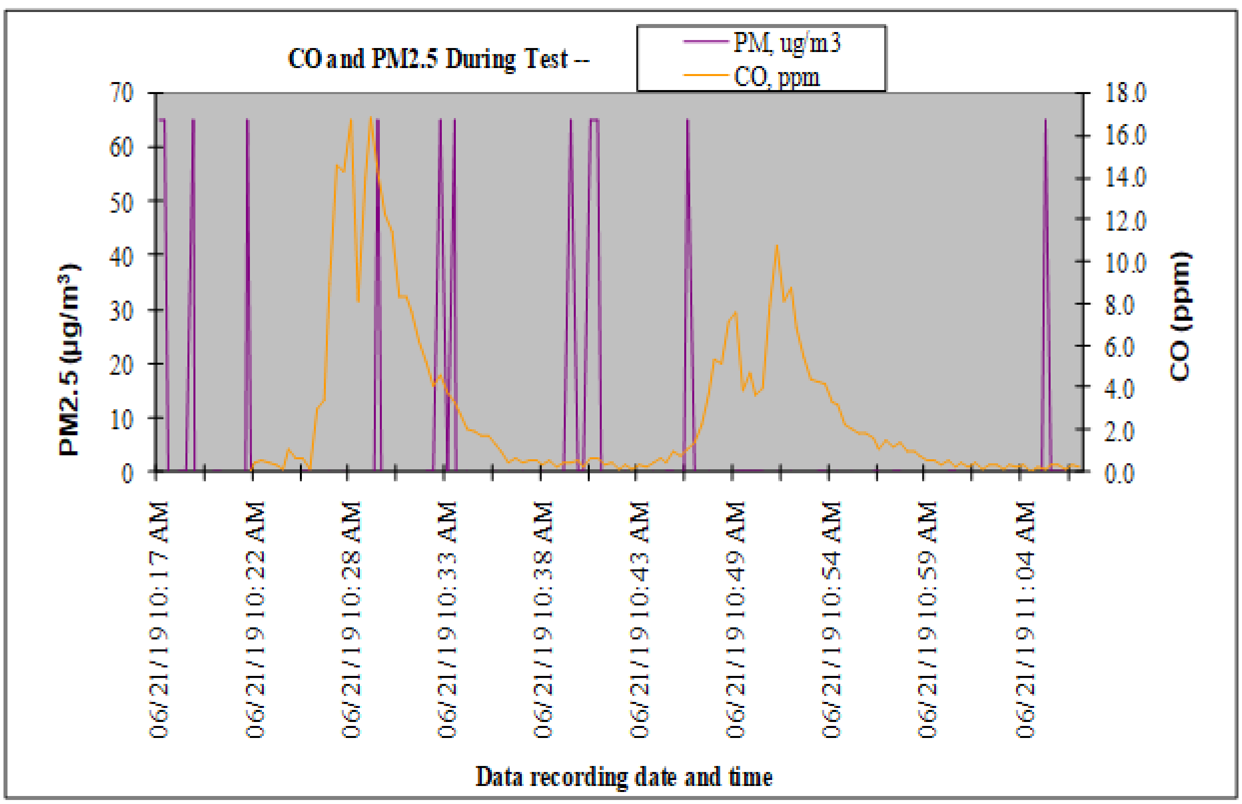


Figure 6

Emission test result of three-stone stove

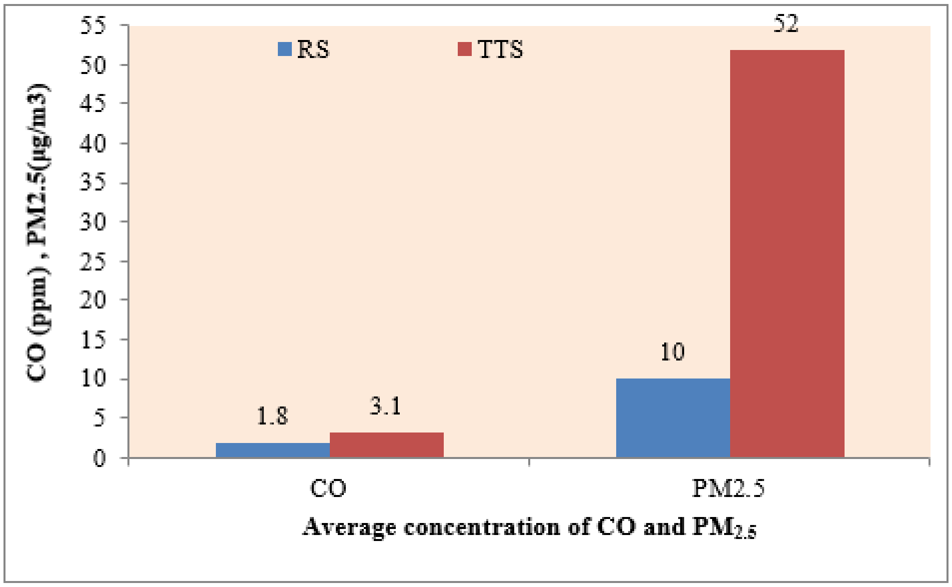


Figure 7

Average pollutant emission of rocket and three-stone stove

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- Methodswithequations.docx