Performance Evaluation of an Improved Cookstove (ICS)

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ABSTRACT

Solid biomass is used mainly as a fuel in the developing world for cooking purposes. Charcoal and firewood are the major types of biomasses used in Sub-Sahara Africa. The traditional stoves used to burn these fuels are inefficient and release a lot of emissions. Past research reveals that rudimentary cooking stoves, combined with inadequate ventilation, emit particulate matter, carbon dioxide (CO_2), and carbon monoxide (CO). The particulate matter is usually emitted in the fine and ultrafine range and harms human health more than coarser particles. Several studies have been conducted to solve biomass sustainability challenges. This study was carried out to fabricate an Improved Cookstove (ICS) and compare its performance with that of a traditional Kenyan metal charcoal stove. The thermal efficiency of the ICS was 31%, whereas that of the metal charcoal stove was 24%. The ICS conserved 38 g of fuel (charcoal) compared to the traditional stove. The firepower, gaseous and particulate emissions were lower for ICS than for metal charcoal stoves.

Keywords: *ICS, traditional metal charcoal stove, thermal efficiency, emissions, firepower, specific fuel consumption*

1. INTRODUCTION

Traditional biomass, such as dung, firewood, charcoal, and other agricultural residues, are used as the primary cooking fuel by 2.9 billion individuals worldwide [1]. In Sub-Saharan Africa, the mostly used biomass is charcoal and wood. These fuels are used by 81% of people for cooking purposes [2]. In Kenya, charcoal and firewood are used by 82% of households [3]. The over-reliance on biomass is attributed to the high cost and scarcity of cleaner cooking alternatives such as liquid petroleum gas and electricity [4]. As such, unprocessed biomass is used widely in low-income households.

The combustion of solid biomass poses severe health implications to its users. The use of open fire or rudimentary cooking stoves combined with inadequate ventilation leads emission of particulate matter and gases, including carbon dioxide (CO_2) and carbon monoxide (CO) [5]. The particulate matter is usually emitted in the fine and ultrafine size range. Past studies have revealed that these particles exhibit diameters ranging from 0.05 µm to 0.2 µm and tend to harm human health more than coarser particles [6]. The emissions lead to indoor air pollution, which causes diseases such as chronic obstructive pulmonary disease, pneumonia, tuberculosis, lung cancer, and heart diseases [7], [8]. The most affected people are women and children. According to the World Health Organization, 2 million people die annually from indoor air pollution [8]. Biomass consumption has threatened the environment as continuous cutting of trees is likely to cause deforestation. Similarly, the CO_2 released during biomass combustion contributes to global warming.

Various stakeholders have promoted interventions to address biomass sustainability. One of the measures is encouraging the invention, fabrication, and adoption of Improved Cookstoves (ICSs). Such stoves possess improved thermal efficiency and reduced emissions [5], [9], [10]. The ICS is meant to replace rudimentary stoves and open fires with high heat losses and emissions. In this study, an ICS was fabricated. Its performance was compared to that of a traditional Kenyan metal charcoal stove. The traditional charcoal stove is fully metallic and has no insulation, hence losing a lot of heat. The study will provide ideas on some modifications that can be done to the traditional stove to improve it.

2. METHODOLOGY

2.1 ICS Description

The ICS shown in Figure 1 was fabricated. It had two zones; hot and cold zones. The hot zone consisted of the pot rest and the firebox. During use, these parts are subjected to the highest temperatures. The cold zone was composed of the shield and body (together with its handles and door). The pot rest and firebox were made of 2 mm mild steel. The material was selected as it is inexpensive compared to stainless steel and more durable than a plain sheet. Mild steel is also malleable, making the fabrication process easier. The grating and secondary air holes were punched using a 15 mm diameter punch. The pot rest was made from a doughnut-shaped part cut with the help of a CNC milling machine. The ICS parts were welded together. This study's insulation material was fibreglass, which was put in the insulation chamber. The cylindrical shape of the body was formed by rolling and attaching the two edges through welding. The shield was also made similarly. The base, door, and handles were welded onto the body.

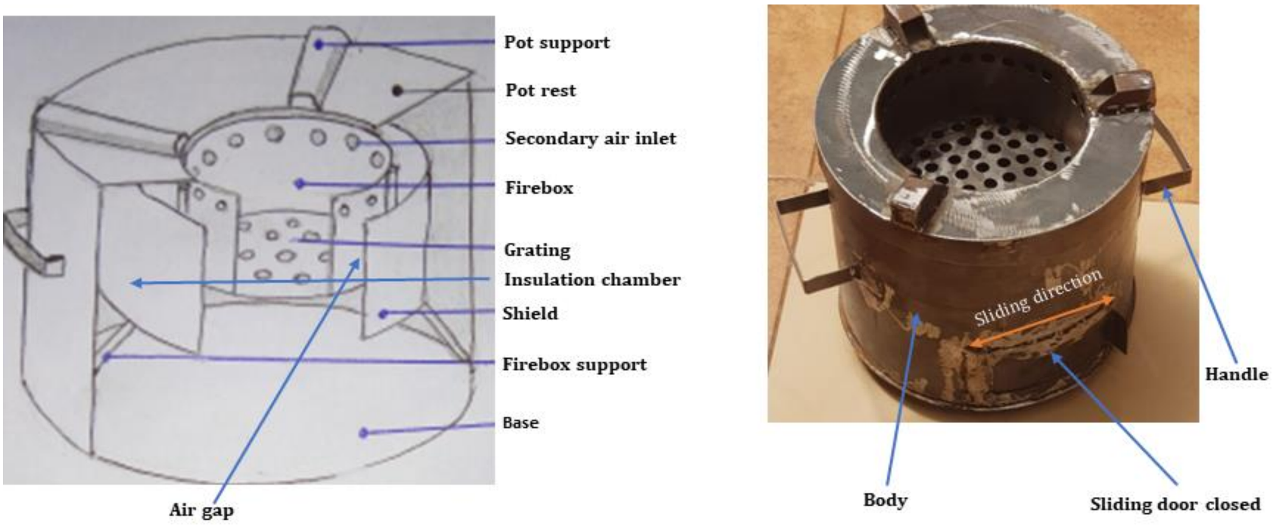

Fig. 1. Parts of the ICS.

2.2 Experimental Procedures

Water Boiling Test (WBT) Protocol version 4.2.3 (from Shell Foundation Household Energy Program) was applied. The stoves samples (ICS and the traditional metal charcoal stove) were evaluated for the time taken to boil 5 litres of water, thermal efficiency, and specific fuel consumption.

Emissions (Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Particulate Matter ($PM_{2.5}$) from the stoves were measured with portable emissions monitors. The traditional metal charcoal stove is shown in Figure 2.

Fig. 2. Traditional metal charcoal stove.

2.2.1 Water boiling test (WBT)

The performance of the stove samples was evaluated using the WBT Protocol version 4.2.3 and following the International Organization for Standardization 19867-1:2018 (E) guidelines for assessing cookstoves' performance. The test was conducted in three phases: the high power (cold start) test, the high power (hot start) test, and the low power (simmering) test.

The high-power phase (cold start) was started by filling two pots with 5 L of water at room temperature. Their temperature and weight were measured and recorded. Fuel (charcoal) sufficient for the phase was weighed and set aside (for both stoves). Four pieces of charcoal were randomly selected from the weighed fuel, and their moisture content was recorded. The fire was started in the stoves at ambient temperature using gelled ethanol. When the fire was lit, the pots with 5 L of water were placed on the stoves. The start time of the cold start phase was recorded.

The fire was tended to bring water inside the pots to boil as quickly as possible. The end time of the cold start was recorded once the local boiling temperature was reached. The pots with water were weighed, and their weights were recorded. Unburned charcoal was removed from the stoves and weighed.

Once the cold phase ended and the stoves were still hot, two pots were filled with 5 L of water at room temperature. Their weight and temperature were noted. Enough charcoal for the hot start and the low power tests was prepared and weighed. The fire was started in the hot stoves, and when the fire was fully lit, the pots with 5 L of water were put on the stove, marking the start of the hot start phase. The starting time was recorded. The water in the pots was rapidly brought to a boil. When the boiling point was reached, the end of the hot start was noted and recorded.

As the hot phase ended, the simmer phase was conducted immediately. The already hot pot, water, and stoves were used in phase 3 of WBT. The unburnt charcoal was removed from the stoves. This fuel was weighed and set aside to be used for the simmer test. The fire was started using the used fuel from the hot phase (phase 2). When the fire was fully lit, two pots containing hot water from the previous phase were put on the stoves, and the start of phase 3 was recorded. The water temperature was recorded. The fire was adjusted to maintain the pot's water temperature close to 3^0C below the local boiling point for 45 minutes. The test finishing time was recorded at the end of 45 minutes, after which the fire was put off while removing the unburnt fuel from the stoves for weighing. The pots and their contents were weighed. The temperature of the water was also measured. The data collected was recorded in the WBT data calculation form.

2.2.2 Emission test

Indoor air concentrations of CO, CO_2, and $PM_{2.5}$ were measured in real-time with portable emissions monitors placed 1m from the stove and 1.5 m from the ground.CO was measured with a monitor using an electrochemical cell; CO_2 was measured using a non-dispersive infrared (NDIR) sensor, while $PM_{2.5}$ was measured with a light scattering photometer.

3. RESULTS AND DISCUSSION

3.1 Thermal Efficiency

The thermal efficiency of the ICS and the traditional metal charcoal stove are summarised in Table 1. As shown, the thermal efficiency of the ICS was slightly improved by 7% (from 24% of the traditional metal charcoal stove). The slight improvement is attributed to using fibreglass as the insulating material. The low thermal efficiency of the traditional metal charcoal stove means that most of the energy/ heat from the stove is lost to the surrounding. The heat loss is attributed to the stove's lack of insulation material. Usually, the traditional metal charcoal stoves are fabricated with bigger fireboxes to compensate for the higher fuel consumption rate caused by high heat losses. However, in this study, the firebox size for the ICS was reduced. More heat is trapped beneath the pot by designing an efficient pot rest that leaves a small clearance between the stove and the pot. This raises the combustion temperature and increases the heat transfer to the pot. Since the efficiency of the stove is improved by the pot rest, there is less need for a bigger firebox. A smaller firebox also means less cost of production as material usage is minimized.

The presence of the secondary air holes on the ICS improved thermal efficiency. Secondary air rose through the air gap (see Figure 1) and was heated by the hot stove. The heated air entered the top of the stove through the secondary air holes. Therefore, the function of these holes was to ensure that the ICS operated as efficiently as possible and released the maximum amount of heat from the burning charcoal.

Table 1. Thermal efficiency

Stove Name	Thermal efficiency (%)
Traditional metal charcoal stove	24%
ICS	31%

3.2 Specific Fuel Consumption.

The amount of fuel (charcoal) used to boil 1 L of water is the specific fuel consumption**.** As shown in Table 2, the ICS used 49 g of charcoal to boil 1 L of water, whereas, in the traditional metal charcoal stove, 87 g of charcoal was used. In this case, there was a conservation of 38 g of fuel with the ICS. The reduction in fuel consumption occurred because a smaller firebox was used.

Table 2. Specific fuel consumption

Stove Name	Specific fuel consumption (g/L)
Traditional metal charcoal stove	87
ICS	49

3.3 Firepower

A comparison of the firepower produced by the ICS and the traditional metal charcoal stove showed a significant difference between the two, as shown in Table 3. The traditional metal stove produced firepower that was higher than that of the ICS. For flame-based cookstoves, a threshold of 5 kW is considered the practical upper limit for domestic cooking [11]. The stoves studied showed firepower that was below this threshold. The lower firepower for ICS suggests that the stove has a slower cooking speed than the metallic stove. The performance of the stoves was observed and showed that the ICS took 36 minutes to boil 5 L of water, whereas the traditional metal charcoal stove took 21 minutes to boil the same amount of water. In this case, the traditional metal charcoal stove had a higher heat flow/heat loss, as evident by the lower thermal efficiency. As such, its firepower was increased. Another reason for the higher firepower is a larger firebox. The metal charcoal stove had a slightly bigger firebox/combustion chamber. As such, more fuel resulted in more power.

Table 3. Firepower results

Stove Name	Firepower (watts)
Traditional metal l charcoal stove	4253
ICS	2898

3.4 Particulate and Gaseous Emissions

The results for particulate and gaseous emissions are summarised in Table 4. As shown, the CO produced by the traditional metal charcoal stove was 40 ppm, whereas that for ICS was 50 ppm. Similarly, the particulate matter for the traditional metal charcoal stove and ICS were 72 µg / m^3 and 75 µg / m^{3,} respectively. These differences in CO and particulate matter emissions between the ICS and the traditional metal charcoal stove are slight. However, there was a significant difference in the carbon dioxide emission (CO_2) between the metal charcoal stove (467 ppm) and the ICS (264 PPM). These results are attributed to the limited oxygen supply to the ICS, which led to incomplete combustion and hence high emissions. This means that the secondary air holes introduced in the ICS slightly improved combustion but did not address the emission problem; more measures should be carried out to deal with the challenge.

Table 4. Particulate and gaseous emissions

Stove Name	CO (ppm)	CO_2 (ppm)	Particulate (µg / m^3)
Traditional metal charcoal stove	40	467	72
ICS	50	264	75

4. CONCLUSION AND RECOMMENDATIONS

An improved cook stove was fabricated in this study. The stove's performance was compared to a traditional metal charcoal stove. The following conclusions were deducted.

1. Fibreglass was used as the insulating material, and the thermal efficiency of the ICS was slightly improved by 7% from that of the metal charcoal stove. Other insulating materials such as rockwool, ceramic blankets, diatomite, and vermiculate should be tested, and an optimal material should be determined.

2. The smaller firebox used in the ICS conserved fuel but lowered the firepower.
3. The ICS design reduced carbon dioxide emissions from 467 ppm to 274 ppm. More improved designs should be generated to lower particulate matter and carbon monoxide emissions.

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