Comparative Analysis of Performance of Locally Used Cookstoves

Peter O. Oketch, Hiram M. Ndiritu and Benson B. Gathitu

Abstract— It is estimated that 2.4 billion people globally rely on biomass as the main source of energy. This has resulted to burning of more than 2 million tones of biomass each day. Improved cooking stove projects in developing countries have been initiated to ensure efficient combustion of biomass. Despite these efforts efficient biomass combustion remains a challenge. Therefore, new technologies have been ongoing to ensure efficient combustion in cook stoves. These include development of new fuels such as bio – ethanol gel which has the potential to reduce deforestation, reduce indoor emissions (that causes health problems) and slow down climate change. For these benefits to be realized stove designs must be developed so as to ensure efficient energy utilization.

In this paper three categories of locally used cook stoves designs were identified and their performance tested. These designs included the bio-ethanol gel stove, Kenya ceramic jiko and the three stone fire configuration. The tests done included the shell water boiling test (WBT) to establish the combustion and energy efficiency. In addition, emission tests were carried out to determine the amount of carbon monoxide and particulate matter resulting from the combustion process involving these designs. It was found that of the three designs, bio-ethanol gel stove had the highest thermal efficiency of 43%. It also had the least amount of indoor emission to the environment. This was attributed to the uniqueness of the design. The results provided insights that would help carry out further design improvements.

Keywords— Biomass, indoor emissions, cook stoves, energy efficiency.

1. Introduction

KENYA is a developing country with a Gross Domestic Product (GDP) of 32.187 billion US dollars as of 2011 [1, 2]. In a population of 38.6 million, 59% live in rural areas with subsistence agriculture dominating the economy [3, 4]. Over the years there has been tremendous population growth in both rural and urban areas, with the urban population predicted to grow as shown in Figure 1.

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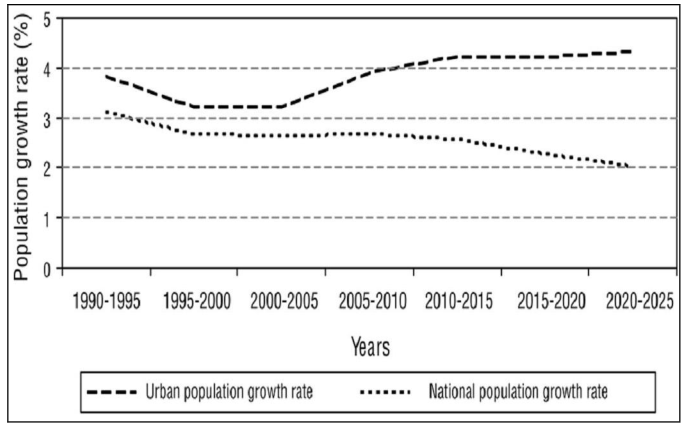

Figure 1: Urban and national population growth in Kenya (1990- 2025) Source: WRI, 2008

The main source of energy in Kenya is biomass that accounts for 70% of the total supply while petroleum products, all imported, account for 21% with electricity constituting 9% of the total energy. Renewable energy is also becoming important although it remains insignificant in the country's overall energy mix [5].

Biomass is the most preferred source of energy by the rural and peri-urban Kenyan. The biomass is supplied in various forms such as wood, charcoal, dung and crop residue. The burning of fuelwood and charcoal results in the emission of pollutants such as particulate matter (PM), carbon monoxide (CO), oxides of nitrogen (NOx) and sulphur dioxide (SO_2). The amount of the pollutant varies, depending on wood type, combustion temperature, stove design and the quantity of oxygen consumed during the combustion process [6].

Carbon monoxide (CO) is one of the primary products of incomplete combustion. Emissions of CO using unimproved fuelwood stoves are frequently as much as 10-15% of the carbon dioxide (CO_2) emissions. Carbon monoxide has a global warming potential (GWP) of 1.9 times that of carbon dioxide [7], and is a large contributor to the localized air pollution in urban areas.

Oxides of nitrogen (NOx) are produced during combustion when combustion temperatures reach a high enough level to burn some of the nitrogen in the air. NOx is an ozone precursor and when dissolved in atmosphere moisture can result in acid rain. Oxides of nitrogen affect atmospheric chemistry in complex ways, including interactions with OH radicals and contributing to ozone chemistry. They are presently thought to be greenhouse-neutral overall [8], and as such the Intergovernmental Panel on Climate Change (IPCC) does not present a GWP for NOx [7].

Particulate matter (PM) is composed of tiny solid or liquid particles. The effect of inhaling PM in human can cause asthma, cardiovascular disease and premature death. All these pollutants have a diverse impact on human health and have been reported to be responsible for 2.7% of the global disease burden and nearly 1.6 million deaths per year [9].

The fuelwood stoves that are mostly used have been found to have a thermal efficiency of approximately 5-17% while the charcoal stoves like the Kenya Ceramic Jiko have a thermal efficiency of 10- 30% [10]. An indication of incomplete combustion and low heat transfer from the stove to the pot. The bio-ethanol stoves are being considered as an alternative to either fuelwood or charcoal stoves. These stoves are considered to reduce CO_2 emission by 69% and have a thermal efficiency of 40-44% such as the SupeBlu stove of Malawi [11].

There is a need for research to improve stove design as well as understand how the operation of the stove can influence its performance in terms of efficiency and emission.

This paper presents the results of a laboratory study using water boiling test to determine the thermal efficiency, fire power and specific fuel consumption of the three stoves (three-stone fire, improved cookstove and the bio-ethanol gel stove) and the emission test to determine the level of emission from each stove.

2. METHODOLOGY

A. Stove description

Three stoves were selected for the analysis. These stoves were the three-stone fire, the Kenya Ceramic Jiko and the bio-ethanol gel stove.

Three-stone fire.

Three-stone fire configuration involves building a fire directly on the ground and placing a pot on top of the three stones that surrounds the fire. Cement bricks that were 19 cm long, 6 cm wide and 6 cm high were used to construct the open fire. The distance between the pot and the floor being about 6 cm. This open fire was well constructed with the bricks having equal distance between them and the sides well protected from wind

Kenya Ceramic Jiko

The Kenya Ceramic Jiko (KCJ) is a portable stove that uses charcoal as fuel. The stove is currently used in over 50% of all urban homes and 16% of rural homes in Kenya and is spreading to neighbouring African countries [12]. This stove has a ceramic liner with 2 cm diameter holes to allow for air flow up through the charcoal. The amount of air is controlled by a small door below the fire in the metal stove body.

Bio-ethanol gel stove

A stove designed to use bio-ethanol gel as fuel that constitutes 76% ethanol, 5% cellulose and 19% water. This stove is a new idea, designed to be a low-cost option for saving fuel while reducing particulate matter.

B. The Assessment of Criteria

The performance of the stoves was based on three main indicators. The indicators were; performance, safety and usability. These indicators covered both qualitative and quantitative data. For each indicator, the bio-ethanol gel stove was assessed relative to Kenya Ceramic Jiko (KCJ) and three-stone fire configuration.

C. Test Methodology

Over the years there have been attempts to define a standard test for cook stoves so that data can be shared and understood on an international level [13, 14]. These test are simple and repeatable in the field hence, need for accuracy to minimize errors that may arise. It's from one of the standard test, the revised Shell/ a modified University of California at Berkeley (UCB) 2003 Water Boiling Test (WBT) that the stoves were subjected to [15]. Also to determine the level of emission a sampling instrument was used to determine the different constituent of the emissions.

The Water Boiling Test (WBT).

The water boiling test (WBT) measures the specific fuel consumption of the stove, the thermal efficiency of the stove and the fire power of the stove. The stoves were tested when started from cold, when fully operational and for 45 minutes simmering three times. There were 2.5 litres (l) of water used in a standard 3 litres pot. The WBT gives a laboratory performance that is useful for design purposes of the stoves; it rarely reflects the true performance of the stove. Thermal efficiency is the ratio of thermal energy used for heating and evaporating water to the energy consumed by burning the fuel. The thermal efficiency is a combination of both the efficiency of combustion as well as heat transfer to the cooking pot. However this is rarely a good indicator of stove performance as it is a measure of the work done to heat and vaporize water, unless steam is part of the cooking process the energy is being wasted. The specific fuel consumption (SFC) is the fuel used to boil one litre of water with test conditions corrected to a standard ambient temperature. The stove firepower is the rate of fuel energy consumed by the stove per unit time (in Watts, W). The set-up for WBT is as shown in figure 2.

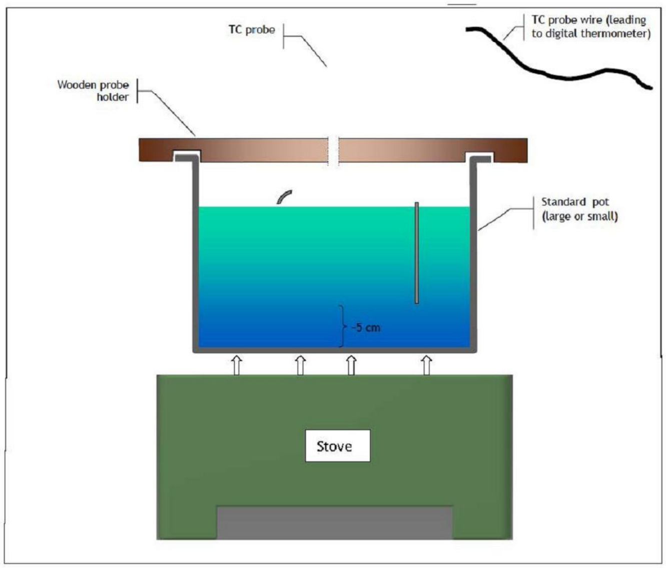

Figure 2: Water Boiling Test

The emission Test

The emission test was done using a sampling instrument (at the Institute of Nuclear Science of University of Nairobi) to determine the suspended total particulate matter (TPM) and gas meters/loggers for the detection of carbon monoxide (CO) and oxides of nitrogen (NOx).

The tests were done in three phases: The first phase involved no activity in the room. The second phase with the stove flaming and the third phase with the stove smoldering. The first phase determines the condition of the room in terms of TPM and presence of gaseous elements while the second and third phase determines the effects of the stove on the room condition.

Test procedure

The two fiber glass filters (coarse and fine) were weighed and loaded on the sampler. The sampler was then switched on and left running for a period of eight hours. The particle loaded filters were removed and weighed to determine the mass of particles deposited. Finally the results were recorded.

III. Analysis and Discussion

A. Performance

From cold start the three-stone fire gave a power of 1.0 kW and thermal efficiency of 10% (Table 1), which was quite low with higher fuel consumption. On simmering the efficiency of three-stone was 17%, an indication that if well controlled the three-stone fire can be effective. From cold start the KCJ took 10 minutes to reach full power, as the charcoal needed time to reach combustion temperature and the ceramic liner absorbed heat. On hot start KCJ took less time with an efficiency of 23%. There was a lot of heat that was stored by the liner that led to difficulties in heat control when simmering. The gel stove took less time from cold start and hot start with higher efficiency but when simmering the gel stove used more fuel than the KCJ.

Table 1: Stove performance

Water Boiling Test	Gel Stove	KCJ	Three-stone fire
2.5L of water in 3L pot			
COLD START			
Thermal Efficiency, %	**40**	**15**	**10**
Duration of phase in minutes	**20.1**	**33.1**	**23.3**
Power (kW)	**1.1**	**2.0**	**1.0**
HOT START			
Thermal Efficiency, %	**43**	**23**	**13**
Duration of phase in minutes	**17.2**	**18.7**	**20**
Power (kW)	**2.5**	**1.4**	**0.9**
SIMMER			
45 minutes, lid off			
Thermal Efficiency, %	**32**	**41**	**17**
Power (kW)	**1.4**	**1.0**	**0.7**
SFC, g/kg Water	**94.4**	**68.3**	**130.4**

The fuel to complete water boiling test was compared and result represented graphically in figure 3. The fuel use is a measure of how efficiently the stove is able to transfer heat into the pot. It shows that the gel stove transfers more heat to the pot followed by the KCJ and last but not the least the three stone fire.

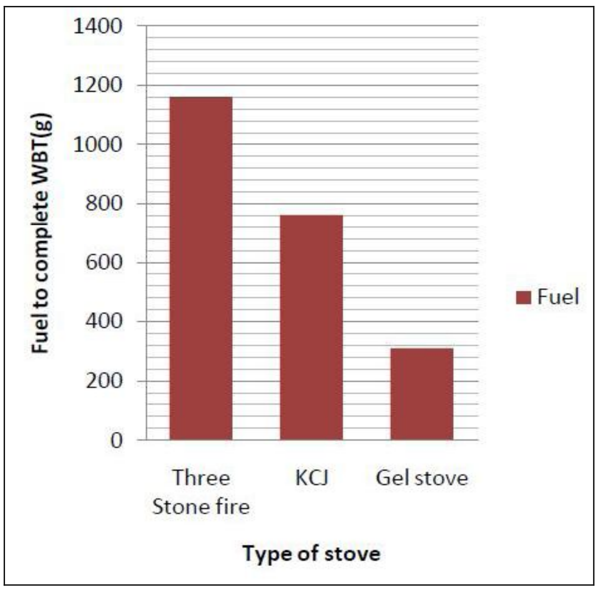

Figure 3: Fuel to complete WBT

3.2 Safety

The bio-ethanol stove is safe in handling as the surface temperature is approximately 60 ^{0}C on the other hand, on the KCJ the ceramic liner can reach temperatures in excess of 300 ^{0}C. The bio-ethanol gel stove emits fewer emissions as compare to both the KCJ and the three- stone fire.

The total particulate matter concentration for the three stone fire was quite high as compared to Kenya ceramic jiko and gel stove hence posing more health effects to the users.

The particulate concentration is reduced by thorough mixing of air, gas and flame in a hot space and by ensuring sufficient draft throughout the stove. Charcoal is appreciated as a low-smoke (PM) fuel and the KCJ (Table 2) made less smoke than the three-stone fire. The gel stove is clean for PM hence low level.

Table 2: PM concentration

Test phase	Size fraction	Atmospheric concentration (μg/m^3)		
		Three-stone	Kenya ceramic jiko	Gel stove
Stove flaming	Fine	294.50	191.15	161.20
	Coarse	450.61	290.51	236.41
Stove smoldering	Fine	99.71	87.82	65.30
	Coarse	496.80	477.32	331.42
No stove activity	Fine	1.51	1.25	1.11
	Coarse	56.72	41.16	37.60

During the WBT, CO emissions were compared during the time to boil and simmer. In all cases CO emissions were high during the time to boil and this was associated with high emissions as a result of starting the fire. The gel fuel had the lowest level of CO emissions (figure 4), an indication that there was sufficient air for complete combustion of the fuel.

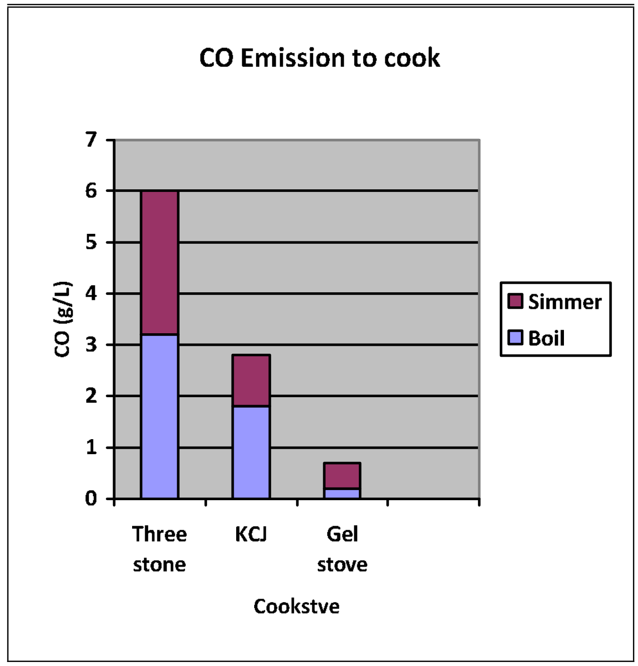

Figure 4: CO Emissions

On comparing CO_2 production, the three stone fire had CO_2 production of 1830 g/kg (Table 3) compared to the gel stove CO_2 production of 1532 g/kg. The amount of fuel used was found to be directly proportional to the CO_2 produced.

Table 3: Carbon dioxide comparison

Stove type	Amount of fuel used (kg)	CO_2 production (g/kg)	CO_2 emission (g/meal)	Comparative emission ratios
Three stone	0.878	1830	1604	339.1
KCJ	0.282	3278	932	197.0
Gel stove	0.292	1532	473	100.0

B. Usability

The KCJ is the most likely stove of choice for low power (i.e. cooking beans or rice) while the gel stove for high power (i.e. making tea and heating water). The KCJ uses less fuel during simmering process hence suitable for low power.

The bio-ethanol gel stove is slowly gaining popularity for its use because of its easy to start, low fuel consumption and low soot level.

Figure 5 summarizes the user's likes and dislikes of the bio-ethanol stove in areas where it has been introduced. This show that majority of the users approved the gel stove for easy to start, less cooking time, easy to clean and turning off. The few disliked it due to difficulty to start outside and the smell of the gel fuel. Hence need to improve stove design and gel fuel smell.

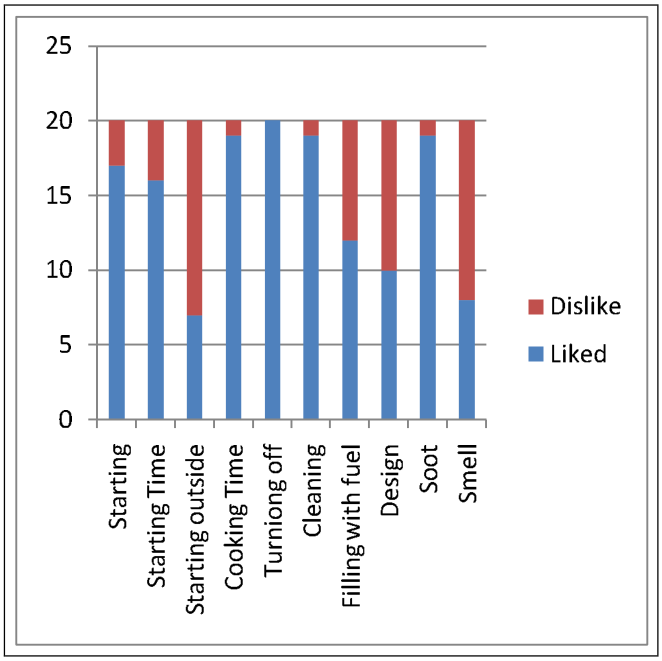

Figure 5: Bio-ethanol gel stove user's likes and dislike

IV. Conclusion

In general, the following results were concluded;

- The gel stove reduced CO_2 emission by 71%, KCJ by 42% in comparison to the three-stone fire.
- The Thermal efficiency of the bio-ethanol gel stove at both high (i.e. 40%-43%) and low power (i.e. 32%) was higher than either KCJ or three-stone fire. The thermal efficiency for bio-ethanol gel (32%) on simmering was less than KCJ (41%). This suggests that gel stove uses more fuel than necessary hence need to design bio-ethanol gel stove that has comparatively high efficiency during simmering.
- The bio-ethanol gel stove was safe to handle since the body temperature was approximately 60 ^{0}C compared to the KCJ whose body temperature could go up to 300 ^{0}C providing risk of burns.

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