Archives of Current Research International

14(4): 1-7, 2018; Article no.ACRI.43498
ISSN: 2454-7077

Thermal Performance and Emission Characteristics of Vented Charcoal Stove

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Authors' contributions

This work was carried out in collaboration between all authors. Author OSO designed the study, performed the laboratory analysis, wrote the protocol and first draft of the manuscript. Authors AAA and ORO performed the AutoCAD drawing managed the literature searches and final analysis of the study. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/ACRI/2018/43498
Editor(s):
(1) Dr. Christopher Koroneos, Associate Professor, Department of Mechanical Engineering, University of Western Macedonia, Greece.
Reviewers:
(1) Arvind Kumar Drave, Indian Institute of Technology Kanpur, Uttar Pradesh.
(2) H. O. Egware, University of Benin, Nigeria.
(3) Monikankana Sharma, Indian Institute of Science, India.
Complete Peer review History: http://www.sciencedomain.org/review-history/26025

Original Research Article

Received 17th June 2018
Accepted 25th August 2018
Published 29th August 2018

ABSTRACT

An improved charcoal stove was designed, constructed and tested in this study to evaluate the thermal performance and combustion efficiency. The evaluation was done in order to know its performance when compared with the commonly found charcoal stove in the locality. Boiling water and rice cooking tests were carried out using the two types of stoves. The time taken, fuel consumption, CO and CO_2 emission were measured during the test in the kitchen. The values of time taking, fuel consumption, CO and CO_2 for improved and local are 86.95 min/kg, 93.17 min/kg; 0.104, 0.093; 11 PPM, 180 PPM; and 478 PPM, 1271 PPM respectively. A better performance was obtained for the improved coal stove in terms of specific fuel consumption and cooking duration. The burning rate for improved coal stove is 0.0129 kg/min and this shows economic and efficient fuel consumption than the other stove that is 0.0155 kg/min. The thermal efficiency of the improved stove is 17.61% while that of the local stove is 16.41%. Also, improved charcoal stove shows better combustion efficiency of 2.3% as against 14.16% for the local stove. There is CO reduction to an acceptable limit of EPA for improved stove while cooking.

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Keywords: Thermal performance; combustion chamber; specific fuel consumption; chimney; charcoal stove.

1. INTRODUCTION

A stove can be defined as a heat-producing device that is employed either for cooking or for generating warmth. A stove generates heat by burning of natural gas, liquefied gases (e.g. Propane, butane), heating oil, bio-fuel (such as wood, coal, corn) or synthetic heating pellets, or electrically, by either electrical resistance (by way of a heating element) or induction [1]. Therefore, a good cooking stove is defined as one that meets technical, scientific, safety, high combustion emissions, ergonomics and structural stability standards [2]. In developing countries where one-third of the world population lives, lack access to modern energy services for their economic and social development and some of their present energy system is unsustainable [3]. Nearly two (2) billion people, constituting about a third of humanity, continue to rely on biomass fuels and traditional technologies for cooking and heating [4,5,6].In developing countries like Nigeria, the majority of households still use charcoal and firewood as the primary fuel for domestic charcoal cooking. Nigeria's forests are therefore under severe pressure from harvesting fuelwood for cooking [7]. Wood is the most affordable and readily available energy source for many low-medium income urban households and rural communities. The majority of these households still depend on the three-stone fire to meet their basic household energy needs [8]. However, these devices have been shown to have poor combustion efficiencies and high pollution emissions of noxious gases and particulates. So, the stove will need a chimney that is able to vent out smoke from combustion. There are problems with modern energy services in Nigeria, for example the electricity supply is erratic, unreliable and a high percentage of the population is not on the national electricity grid, the high price of gas makes it out of reach of the common man, the solar energy which could serve as another source of energy is location specific, fluctuating, inadequate technology for harnessing it and has associated storage problem and lastly perennial fuel crisis. Thus, using modern energy sources for cooking is a problem for the majority of household in Nigeria.

Although coal stands out as an affordable, available and safe to store resources that are relatively easy to employ for domestic cooking, the use of coal in inefficient stoves that waste resources and produce substantial amounts of indoor air pollution would be unsustainable. However, continual technology development will tame coal's disadvantages and allowed coal to be used with much greater efficiency and greatly reduced environmental impact [9]. Traditional fuels such as biomass are quite difficult to burn completely in the simple household-sized stove. The use of these fuels has a negative impact on the health of household members, especially women and children when burned indoors without either a proper stove to help control the generation of smoke or a chimney to vent the smoke outside [3]. Traditional cook-stoves cause indoor concentrations of important pollutants, such as carbon monoxide, benzene and formaldehyde. Such exposures are linked to acute respiratory infections, chronic obstructive lung diseases, low birth weights, lung cancer and eyes problems [10,11].Therefore, the accelerated technological effort is required to improve coal-stove and coal's environmental performance.

When incomplete combustion occurs during wood firing, smoke is released. The harmful substance released in smoke is Carbon Monoxide. The World Health Organization (WHO), estimates that more than 1.5million people die annually due to smoke from the combustion of solid fuels [12], and according to reports by the International Center for Energy, Environment and Development (ICEED), Nigeria experiences one of the highest numbers of smoke-related deaths in the world [13]. In a poorly ventilated room during wood combustion, it is extremely easy to accumulate Carbon Monoxide to dangerous levels. An American organisation, the Environmental Protection Agency (EPA) describes a safe level for the amount of Carbon Monoxide in the air, which many uses as a standard. The EPA describes "good" air with less than 9 parts per million (ppm) of Carbon Monoxide in the air. They describe "fair" air with 9 to 15 ppm of Carbon Monoxide (CO) in the air. Concentrations of over 15 ppm of CO in the air are deemed as "poor". An indoor fire has concentrations of around 160ppm of CO, making it extremely unsafe [14]. Although the solution to indoor air pollution would have been the use cleaner liquid and gaseous fuel the population of the users of coal and wood are poor and therefore, improved biomass-fired stove will remain a best alternative option for many years to come [2].

The development of charcoal burning stove is not a recent development, several improvement works have been done on the stove design. Apart from the economic and environmental considerations, the other main issue which motivates the various developmental efforts of the charcoal stove is the health factor [15,16]. Most work reported by researchers were on how to improve the thermal efficiency of the charcoal stove by varying the configuration but little reports are on the emission rate of the stove [17,18,19,20,21,22].

This study is on how to use locally available materials to develop efficient, improved, safe burning charcoal stove with provision for a reduction in heat loss to the kitchen environment and indoor pollution. This paper also presents a comparative performance analysis of improved charcoal stove and traditional charcoal stove.

2. MATERIALS AND METHODS

Experiments were conducted in a kitchen. The purpose of this is to allow proper reading to be taken during the experiment. Two types of metal stoves were employed in this experiment. The first is the common type of charcoal stove in the community that was fabricated in a mechanical workshop in LAUTECH, Ogbomoso. It has a burning and heating section that has a frustum shape (27 x 27 cm at the top and 15 x 15 cm at the base and height 10.8cm) and a square base (13 x 13 cm) that is closed at the bottom for ash collection as shown in Fig. 1. The second type is fabricated to control air pollution and the rate of heat dissipation in the kitchen (Fig. 2). The stove is made up of mild steel with a rectangular shape (41 x 34.5 cm and height 53.7 cm) that is lagged with fibreglass of thickness 3cm. It has a combustion chamber, a top section and the base. The burning section of the combustion chamber has a tray made of mild steel that is grated to allow air for proper combustion of charcoal. There are openings at the base of the door to combustion chamber which will allow adequate air into the chamber for proper burning. There is also a facility for ash collection at the base of the chamber. The combustion chamber has a circular opening for the chimney (of 2 cm in diameter) to vent smoke and other by-product out of the chamber and kitchen. The chamber is lagged with fibreglass (3cm thickness) to prevent heat loss into the cooking space. The height of the chimney from the side of the combustion chamber is 25 cm and is connected to an outlet pipe. The top of the stove consist of pot seat (circular with a diameter of 17 cm) that is perforated to allow heat get to the bottom of the pot. The pot seat is designed to allow the pot to seat and cover the heating space to prevent heat loss. There is a provision of baffles to allow for retention of heat in the combustion chamber.

Carbon dioxide, carbon monoxide and oxygen concentration were measured using an air quality meter (Model: AQ-9901SD). The initial quality of air inside the kitchen was measured. Also, air quality during the experiment and after the experiment was measured.

Fig. 1. local stove

Fig. 2. Improved stove

2.1 Theoretical Analysis

Thermal Efficiency: How efficient heat is transferred from the fuel to the pot will determine the value of the thermal efficiency [23]. Maximum heat transfer will be achieved as a result of how close the pot to the heat source. The method used to calculate the thermal efficiency are based on the procedure used by [23,24,25,26].

The burning rate, R, corrected for the moisture content of the fuel was calculated using Eq. (1):

$$R(kghr^{-1}) = \frac{100(W_i - W_f)}{(100 + M)t} \tag{1}$$

Where:

W_i = Initial weight of fuel at the start of the test, kg;
W_f = Final weight of fuel at end of the test, kg;
M = moisture content of fuel, %;
t = total time taking for burning fuel, hr.

Thermal efficiency η_{th}, the calculation was done by substituting the values of burning rate, the net calorific value, Q_{net}, of the fuel, used according to equation (2):

$$\eta_{th} = \frac{W_{wi}C(T_f - T_i) + (W_{wi} - W_{wf})L}{R \times t \times Q_{net}} \tag{2}$$

where:

W_{wi} = initial weight of water in the pot, kg;
W_{WF} = final weight of water in the pot, kg;
T_i = final temperature of water, °C;
T_f = initial temperature of water, °C;
C = specific heat capacity of water, kJkg–1K–1;
L = latent heat of vaporization of water at 100°C, kJkg–1.

2.1.1 Specific fuel consumption

The specific fuel consumption (SFC) is expressed as

$$SFC = \frac{\text{Mass of consumed fue}}{\text{Total mass of cooked food}} \tag{3}$$

$$SFC = \left[\frac{W(1-M) - 1.5W_f}{m_{pf} - m_p}\right] \tag{4}$$

Where,

W = Mass of fuel (W_i -W_f),kg
m_{pf} = Mass of pot with cooked food, kg
m_p = Mass of pot, kg
M = Moisture content of charcoal, %

2.1.2 Performance evaluation

The performance of improved charcoal stove and the traditional stove was evaluated by setting them up in the kitchen and a number of tests were carried out on the two stoves. The apparatus used for the tests included two medium-size aluminium pots, a weighing balance, a stopwatch, thermometer, air quality meter, kerosene and matches.

2.1.3 Tests on burning rate

The two types of stoves were used for burning rate test. Adequate charcoal for the test was charged into each stove and the initial weight of fuel at the start of the test, the final weight of fuel at the end of the test and the time for each experiment were recorded. This test was repeated two more times for the two stoves and the average burning rate value was calculated for each of the stoves.

2.1.4 Water boiling tests

The simple, short and standard cooking procedures are Water Boiling Tests (WBTs) [24]. The fuel consumed and time required for simulated cooking were measured. WBTs are usually employed to investigate the performance of the stove under different operating conditions to an expected stove performance. It is used by stove designers, researchers and field workers for quick comparison of the performance of stoves. The data obtained were used to compute the thermal efficiency for each stove using Eq. (2).

2.1.5 Controlled cooking test

The cooking test was done to compare fuel consumed and the time spent to cook food on different types of stoves. The two types of the stove were used to cook rice and the specific fuel consumption, which expresses the amount of fuel required to cook 1 kg of food. The cooking pots were weighed after which 0.4 kg of food was put in each pot which already contains 1.5 L of water. The weights of fuel in each of the stoves before and after the test were recorded. The data collected were used in calculating the specific fuel consumption (SFC) and time spent to cook 1 kg of food.

$$\text{Time spent per kg of food} = \frac{T_c}{M_f} \quad (5)$$

Where;

T_c = Total time spent in cooking;
M_f = Total mass of cooked food

3. RESULTS AND DISCUSSION

3.1 Results

The results obtained from the experiment for water boiling and rice cooking are presented in Tables 1 to 4.

3.2 Discussion of Results

The burning rate obtained for the two stoves were 0.0129 kg/min, 0.0155 kg/min for improved coal stove and traditional stove respectively. This result shows that the traditional coal stove had the highest burning rate than improved coal stove. Burning rate determines the how much fuel is consumed during combustion, the higher the burning rate the quicker the fuel will be used up. High burning rate implies that the quantity of fuel that will be used for a particular task will be high and this is not economical. This is to confirm that traditional stove will waste more fuel and hence there is a need for improvement to make it economical.

The thermal efficiencies obtained from the improved coal stove and traditional coal stove

Table 1. Test results for water boiling

Parameters	Water boiling	
	Improved stove	**Local stove**
Mass of pot (kg)	0.307	0.307
Initial mass of fuel (kg)	0.748	0.748
Final mass of fuel (kg)	0.644	0.655
Mass of fuel consumed (kg)	0.104	0.093
Initial temperature of water (^{o}C)	28.8	28.8
Final temperature of water (^{o}C)	99	99
Initial mass of water (kg)	1.0	1.0
Final mass of water (kg)	0.96	0.93
Duration of boiling water (min)	8	6
Specific fuel consumption	0.104	0.093
Burning rate (kg/min)	0.0129	0.0155
Thermal efficiency (%)	17.61	16.41

Table 2. Combustion efficiency for the two types of stove

	Water boiling		Rice cooking		Initial room condition
Parameters	**Improved stove**	**Local stove**	**Improved stove**	**Local stove**	
CO (PPM)	11	180	11	380	10
CO2 (PPM)	478	1271	685	1246	347
CO/CO2 = Combustion efficiency	0.023 =2.3%	0.1416= 14.16%	0.016 =1.6%	0.3046 =30.46%	

Table 3. Time spent in cooking

Type of stove	Time spent in cooking 0.161kg of rice (min)	Time spent in cooking (Min/kg of rice)
Improved coal stove	14	86.95
Traditional stove	15	93.17

Table 4. Specific fuel consumption for rice and water

Type of stove	Rice	Water
Improved coal stove	0.23	0.104
Traditional stove	0.20	0.093

were 17.61% and 16.41% respectively. The stove with higher thermal efficiency shows minimal loss of convective heat. Higher burning rate leads to lower thermal efficiency.

The time taken to cook 1 kg of rice on an improved coal stove and traditional coal stove were 14 and 15 min respectively (Table 3). The result shows that improved stove cooks faster than a traditional stove. The specific fuel consumption of improving coal stove and traditional coal stove for cooking rice was 0.23 kg/kg and 0.20 kg/kg respectively (Table 4). The local coal stove shows better performance than the improve coal stove because, in the process of preventing carbon monoxide concentration, heat transfer to the base of the pot has reduced.

Combustion efficiency as shown in the Table 2 confirms that the improved stove has good combustion efficiency than the local common stove for both water boiling and rice cooking. The values are 2.3% and 14.6% (water boiling) and 1.6% and 30.46% (rice cooking) for improved and local stoves respectively.

Carbon monoxide concentration by using traditional stove is more than acceptable EPA limit. This is to confirm that the improved coal stove has been able to reduce carbon monoxide concentration to an acceptable limit. This also will reduce health-related problems and death as a result of carbon monoxide concentration. The introduction of lagging to improved stove has helped in terms of even heat distribution in the combustion chamber and therefore, improves the performance.

4. CONCLUSION

In this work, charcoal stove that has good thermal performance than the common charcoal stove has been designed and fabricated. The carbon monoxide emission for improved charcoal stove has been greatly reduced due to the provision of the chimney to meet EPA standard. This will not expose the user to health risk. The improved stove was lagged thereby reducing the heat transfer to the kitchen space. The combustion efficiency of the improved stove has been improved.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sciencedomain.org/review-history/26025