Nigerian Research Journal of Engineering and Environmental Sciences 2(2) 2017 pp. 351-359

Nigerian Research Journal of Engineering and Environmental Sciences
Journal homepage: www.rjees.com

Original Research Article

DESIGN AND CONSTRUCTION OF A BIOMASS STOVE FOR COOKING IN RURAL SETTLEMENTS IN NIGERIA

[1]Igboanugo, A.C. and *[2]Ajieh, M.U.

[1]Department of Production Engineering, Faculty of Engineering, University of Benin, Benin City, Nigeria
[2]National Centre for Energy and Environment (Energy Commission of Nigeria), Benin City, Nigeria
*mike.ajieh@gmail.com

ARTICLE INFORMATION

Article history:
Received 20 December, 2017
Revised 25 December, 2017
Accepted 26 December, 2017
Available online 29 December, 2017

Keywords:
Biomass stove
Thermal efficiency
Fuel wood
Three-stone fire
Fuel consumption

ABSTRACT

An improved biomass stove was designed, constructed and its performance was evaluated. The uniqueness of the stove is its portability, and insulated combustion chamber. In addition, a conical flame collector was introduced with vents for ease of circulation of primary and secondary air. Stove performance was based on the heat transfer efficiency, percentage heat utilized, fuel consumption and burning rate. Water boiling test was conducted in accordance with University of California Berkeley (UCB)/Shell Foundation method which is based on ISO/IWA/VITA WBT 4.1.2 standards for testing the efficiency of wood in stoves. The improved biomass stove (IBS) had a maximum thermal efficiency of 55% compared to 18% for the traditional three-stone stove while the percentage heat utilized (PHU) was 54%. The introduction of secondary air inlet through the combustion chamber enhanced heat retention and increased fire power during cooking.

1. INTRODUCTION

Open fires and primitive stoves have been used for cooking since the beginning of human history. These stoves have come in various sizes and shapes which require biomass as feedstock. Nearly 2 billion people, constituting about a third of humanity, continue to rely on biomass fuels and traditional technologies for cooking and heating (Momoh and Soaga, 1999). Apart from lack of improved technologies, the present practice is unsustainable (Smith, 1993). In addition, the seemingly unending perennial fuel crisis in Nigeria has drawn attention to the need for energy experts to concentrate on producing viable alternatives to kerosene and cooking gas for domestic cooking (Olorunisola, 1999). While many developed countries tend to focus on domestic energy security or decarbonizing their energy mix, developing countries are still seeking to secure enough energy to meet basic human needs. In developing countries, access to affordable and reliable energy services is fundamental to reducing poverty and improving health, productivity, enhancing competitiveness and promoting economic growth. Despite these, billions of people are without basic modern energy services, lacking reliable access to either electricity or clean cooking facilities. The aim of this work is to improve the thermal efficiency of open fire otherwise known as three stone stove to a more energy conserving stove.

Improved stoves are designed to increase fuel efficiency and reduce smoke and harmful emissions associated with the combustion of biomass fuels. In this work, natural convective force was created in inform of primary and secondary air inlet to improved thermal efficiency and heat transfer (Baldwin, 1987). Though poor combustion will negatively affect a stove's thermal performance, it is not as significant a factor as heat transfer efficiency. Energy losses due to incomplete combustion resulting in the emission of carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NOx), smoke and soot (Ndiema *et al.*, 1998). Improved stove designs seek to increase combustion efficiency through a number of design features. Adequate draft and a proper air-to-fuel ratio ensure a more complete and efficient combustion process. Careful consideration of the size, geometry, and placement of the fuel inlet and combustion chamber provides increased control of airflow. A hotter fire is also more effective at consuming combustible gases. Proper insulation around the combustion chamber reduces heat loss, allowing the fire to burn at higher temperatures (Bailis *et al.* 2009).

There exist several researches on biomass stoves, aside the economic and environmental considerations, the other main reason motivating the various developmental efforts in the design of biomass stove is the health factor (Joseph *et al.,* 1990; Karekezi, 1992). In Nigeria, there is the popular mud stove which is similar to the Kilakala stove in Tanzania (Crewe, 1990; Otiti, 1991). One of the major disadvantages of the mud stove is that it is not movable. The Kenya Ceramic Jiko (KCJ), one of the most successful urban stove projects in the Eastern African region, was reported to have a useful heat of about 25-40 % of the heat generated (Kammen and Fayemi, 1992). KCJ represents a significant improvement over the three-stone open fire which directs only about 5-10% of the heat generated from the fire to the cooking pot. One of such research attempts is the two-pot stove which is similar to the Improved Vented Mud stove (IVM) with chimney. The IVM also called the Nada Chula was developed in India and has average thermal efficiency values between 10 to 23.5%. The version of (IVM), made of ceramic lining with mud coating which is called the Improved Vented Ceramic (IVC) has higher efficiencies for all fuels except crop residues. George (1997) found the thermal efficiency of the Traditional U-shaped Mud (TUM) stove made of locally available clay and coated with cow-dung clay mixture to have an average thermal efficiency of 17.9%. There are several other works on biomass stove most of which operates at average thermal efficiency ranging from 5 – 20%. In a similar design, Ayo (2009) obtained a thermal efficiency of 64.4% for an improved wood stove, although slightly bigger and heavier than the conventional portable kerosene stove.

The uniqueness this Improved Biomass Stove (IBS) is its size and portability, it is a rocket stove in accordance is an improved stove design developed by Larry Winiarski and the Aprovecho Institute in 1982. The stove incorporates an L-shaped combustion chamber and pot "skirt" to improve heat transfer and combustion efficiency during cooking activities. The combustion chamber consists of a horizontal fuel magazine and vertical internal chimney. Wood is fed horizontally into the fuel magazine ensuring even combustion from one end and a more easily regulated feed rate. The internal chimney creates draft, accelerating combustions gases from the fire. These gases are then forced through the skirt that surrounds the cook pot. Greater convective heat transfer is the result of improved advection and increased surface area contact. The IBS is designed for portability and uniform cross sectional area throughout the stove in other to enhance draught and combustion. This design also reduced the gap between the pot suspender and the pot to minimize heat losses as well serve as internal chimney. Fiber glass was used as insulator between the internal wall of the combustion chamber and the external wall for ease of handling. Conical flame connector was introduced to reduce heat losses and associated particulate emissions.

2. METHODOLOGY

2.1. Description of the Stove

Figures 1 to 7 are component drawings of the stove. The stove consists of a combustion chamber, a top section and a base. The combustion chamber is encased in mild steel fitted with fiberglass. The fuel bed or reservoir as shown in Figure 6a is cylindrical shaped and placed inside the stove where combustion of the fuel takes place. The stove cover (Figure 6a) is mounted on the cylindrical component to enhance heat retention during cooking. The ash filter (Figure 1b) consists of holes of 2cm diameter through which ashes escape to the ash collector. The flame connector (Figure 3a) is welded to the upper chamber of the cylindrical cone, to concentrate the heat released to the pot. An L-shaped pot suspender (Figure 2b) is attached to the ring top of the stove to reduce heat loss during cooking. The pot suspender has external and an internal diameter of 20 cm and 19 cm respectively (Figure 2b). The suspender is responsible for keeping the pot in position and also create interface between the heat released and the pot. The fuel feeder is a rectangular grove created to allow fuel and air inlet and to ensure that smoke associated with the heat is released before it reaches the pot. A drawer (Figure 1a) is incorporated at the base to facilitate the removal of ash and collected at the tray. The ash filter is a metal frame, its function is to hold the fuel in position and, filter off the fuel ash that is collected and used for crop cultivation. It is made from a mild steel sheet of 2 cm thick. Sufficient holes were drilled on the plate for easy air passage. The ash filter is 25 cm in diameter and supported by rods welded to the plate. The stove housing (Figure 6a) is 20 cm in external diameter and 19cm internal diameter; welded to it is a 5 cm × 4 cm L-shaped auxiliary that is mounted on the stove cove. A cone-like structure with circular holes was created in it with height of 15 cm, 25 cm diameter and an upper diameter of 15 cm made up of steel materials welded to the housing unit with many holes drilled in it for ease of circulation of secondary air. The stove frame was fabricated from stainless steel sheet of 20 mm thickness; it is a hollow cylinder of 500 mm in height and 200 mm in diameter. Two handgrips are attached to the stove housing to ease carriage. The ash dissipated from combustion is filtered off and collected with the ash collector.

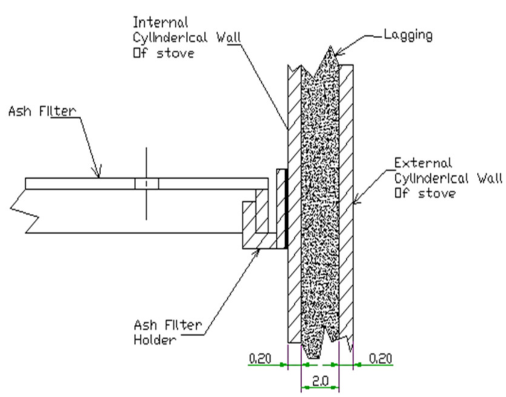

Figure 1a: Ash filter frame

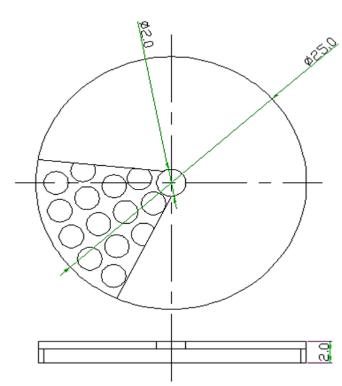

Figure 1b: Ash Filter with holes

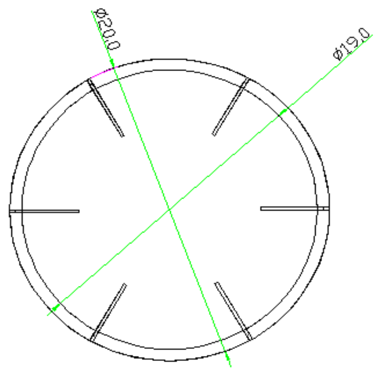

Figure 2a: Pot suspender holder

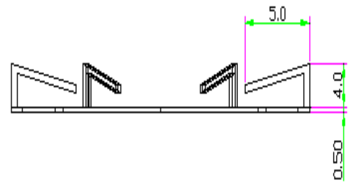

Figure 2b: Pot suspender

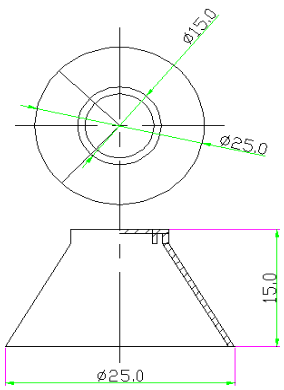

Figure 3a: Flame connector

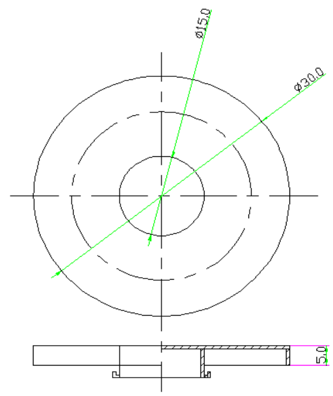

Figure 3b: Flame connector cover

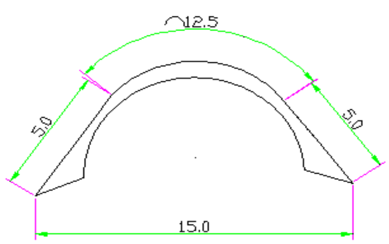

Figure 4a: Stove handle

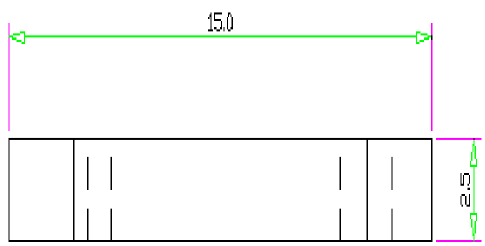

Figure 4b: Handle holder

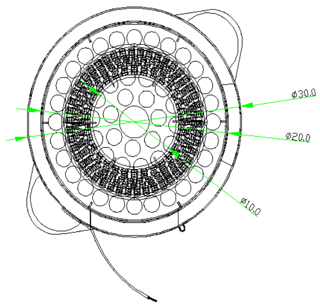

Figure 5a: Ash collector

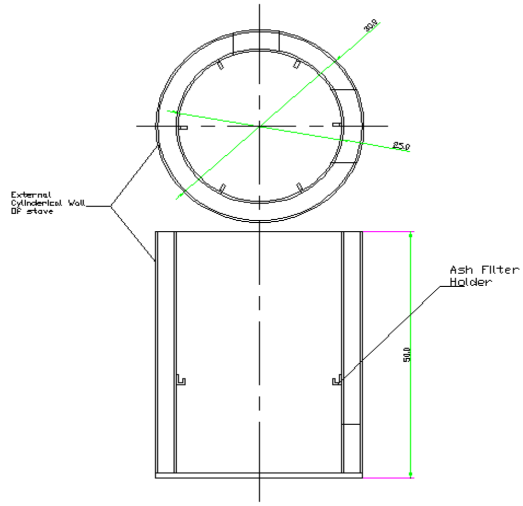

Figure 5b: Stove frame

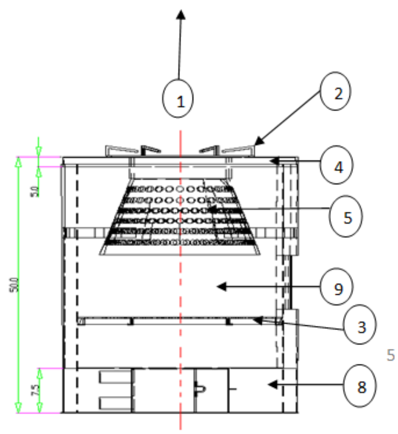

Figure 6a: Stove housing

Table 1: Parts description for Figure 6a

Item No.	Item Description
1	Ash chamber ate
2	Stove cover
3	Ash filter
4	Pot suspender
5	Flame connector
6	Handle
7	Fuel gate
8	Ash collection unit
9	Fuel reservoir

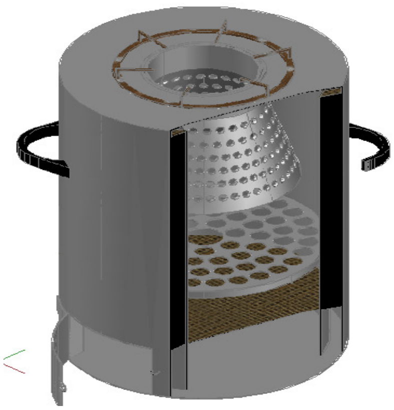

Figure 7a: Solid frame

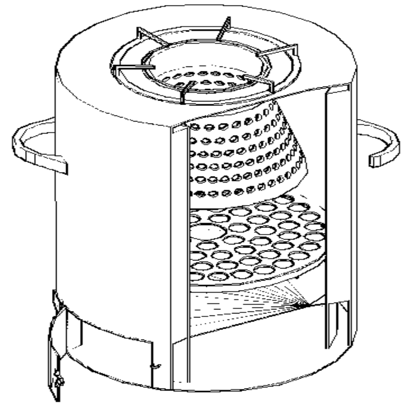

Figure 7b: Wire frame

The diameter of the combustion chamber is such that it is smaller than the pot seat or the external diameter of the smallest pot that can be used on the stove to ensure that the maximum amount of heat is transferred to the pot. The height of the flame connector is adjusted to allow for enough time for the combustion of the burning fuel before it reaches the base of the pot on the stove.

2.2. Water Boiling Test

Water boiling test (WBT) was carried out to test the performance of the stove in an enclosed kitchen environment in accordance with University of California Berkeley (UCB)/Shell Foundation which is based on ISO/IWA/VITA WBT 4.1.2 standards for testing the efficiency of wood on stoves. The materials used for this test include: scale (to measure the weight of fuel and pot), heat resistant pad to protect the scale, digital thermometer, stop watch, test pots and heat resistant glove. In this test, considerations were given to heat losses which may result from poor insulation. Woody biomass was selected in accordance with Akinola and Fapetu (2015) on the heating value of some indigenous wood. The pot, lid, and digital thermometer were weighed, and then a measured amount of water by volume (about two-thirds the pot capacity) was added to the pot and weighed again to determine the weight of the water. Weighed fuel wood was introduced into the combustion chamber and ignited. The fire was allowed for 5 – 10 minutes to ensure consistent burning rate before the weighted water and pot was placed. The time, temperature of the surrounding and the initial temperature of the water were noted. Water temperature was measured at interval of 2 minutes until boiling temperature was reached. At the boiling point, the fire was put out, and the remaining fuel wood and the water re-weighed.

2.3. Design Analysis of the Stove

The heat loss across the cylindrical wall of the heating chamber is expressed by Fourier's law:

$$Q_r = -KA\frac{dT}{dr} \quad (1)$$

K is the thermal conductivity of the cylindrical walls; A is the area and $\frac{dT}{dr}$ is the radial temperature gradient across the wall. At steady state, heat flow Q_r is independent of r and $T_i > T_o$
Integrating Equation (1) results in:

$$Q_r = \frac{T_i - T_0}{\frac{1}{2\pi Lk} ln\left(\frac{r_0}{r_i}\right)} \quad (2)$$

For composite cylinder with known inside and outside surface temperature with *n* layers of different materials:

$$Q_r = \frac{T_1 - T_{n+1}}{\frac{1}{2\pi L}\sum_{i=1}^{n}\frac{1}{K_i} ln\left(\frac{r_{i+1}}{r_i}\right)} \quad (3)$$

Thus, for a composite cylinder with radii, r_1, r_2, r_3, and r_4 as shown in Figure 8.

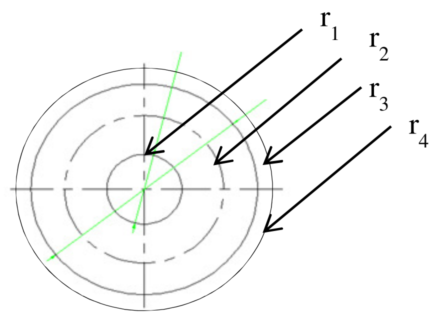

Figure 8: Cross-sectional view of composite cylinder

From Figure 6a and 8 respectively, height of the combustion chamber, L_{cc} = 200mm; internal radius of combustion chamber, r_1 = 35mm; internal radius of insulation lining, r_2 = 75mm; internal radius of mild steel casing, r_3 = 115mm; external radius of mild steel casing, r_4 = 120mm; height of side air vent, h = 25mm; height of stove base, H_{sb} = 50mm; external diameter of pot seat chamber, D_{ps} = 160mm; height of pot seat chamber, H_{ps} = 25mm; measured external temperature of combustion chamber, T_o = 32^{o}C; measured Internal temperature of combustion chamber, T_i = 250^{o}C, thermal conductivity of fiberglass, K_1 = 0.037W/mK; thermal conductivity of mild steel, K_2 =39W/mK.
Heat loss Q_r across the cylinrical wall is 13.3W.

2.3.1. Thermal efficiency of stove

Thermal efficiency is expressed as:

$$Thermal\ Efficiency = Burning\ Rate\ \times Percentage\ Heat\ Utilized \quad (4)$$

The burning rate can be expressed as:

$$Burning\ Rate\ (F) = \frac{1}{t}\left[\left(\frac{100 \times M_f}{100 \times X}\right) - \left(\frac{M_c \times H_c}{H_w}\right)\right] \quad (5)$$

X is the moisture content of fuel, H_c is the calorific value of charcoal, H_w is the calorific value of fuel and *t* is the time it takes to reach the boiling point.
But, the Moisture Content (X) for dry fuel is expressed as:

$$Moisture\ Content\ (X_{dry}) = \frac{(Mass\ of\ fuel)_{wet} - (Mass\ of\ fuel)_{dry}}{(Mass\ of\ fuel)_{dry}} \times 100 \quad (6)$$

Where M_{wet} is 0.5 and M_{dry} is 0.4962, hence, *X* = 0.8% and the burning rate per minute *F* = 1.03

Percentage Heat Utilized (PHU) is computed from:

$$PHU = \left[\frac{(M_w C_w + M_p C_p)(T_f - T_i) + M_v L_v}{M_f C_f - M_c C_c}\right] \times 100 \quad (7)$$

C_w is specific heat capacity of water, C_p the specific heat capacity of pot, C_f is the specific heat capacity of fuel, C_c is the specific heat capacity of charcoal and L_v is the latent heat of vaporization of water.

3. RESULTS AND DISCUSSION

Water boiling test was used to measure the overall performance of a cook stove. Table 2 shows the WBT result. Substituting the parameters into Equations 4 and 7, the Percentage Heat Utilized (PHU) is 53.8% and the Thermal Efficiency is 55.4%. This indicates a considerable improvement when compared to the average thermal efficiency value of 17.9% for traditional mud stove and IVM stove of 10-23.5%. Furthermore, the thermal efficiency of U-shape mud stove is 17%. Ayo (2009) designed a biomass stove with thermal efficiency of 64%. However, this stove has an advantage of size, portable and adapted to the shape of the conventional kerosene stove which makes highly socio-culturally preferred. The increase in thermal efficiency can be attributed to a number of factors which are; insulation of the combustion chamber with fiberglass to minimize heat loss across the walls of the chamber through conduction and radiation, introduction of conical flame connector to arrest most of the heat generated to the pot and provision of sufficient cross ventilation of primary and secondary air. Apart from its flexibility with in-built chimney when compared with other chimney stove, it can be used with fuel pellets/briquettes other than fuel wood. On particulate emissions, the improved cooked stove performance shows noteworthy reduction when compared with traditional three-stone fire. The three-stone fire required more attention to operate than the biomass stoves tested. Other impressive areas of the improved biomass stove are; reduction in cooking time, percentage heat utilized, lightweight, lower cost on mass production and ease of operation.

Table 2: Water boiling test parameters

Test Parameters	Measured Values
Ambient temperature	32 ^oC
Initial water temperature, T_i	32 ^oC
Final water temperature, T_f	100 ^oC
Time to reach boiling point, t	10 mins.
Weight of empty pot, M_p	0.54 kg
Initial weight of fuel wood, M_f	0.5 kg
Weight of charcoal after boiling, M_{cb}	0.35 kg
Initial weight of water, M_w	2.5 kg
Final weight of water, M_{fw}	2.08 kg
Weight of water evaporated M_v	0.42kg

4. CONCLUSION

The improvement made on the design through the provision of insulation around the combustion chamber, introduction of sufficient channels for up-draught of primary and secondary air and incorporation of a conical flame connector have contributed to significant increase in the thermal efficiency and the percentage heat utilization of the stove. There has also been a drastic reduction in the smokiness of the stove, making it to be more user-friendly, more comfortable and convenient. Apart from ease with cooking, it reduces time spent on cooking and emission of gaseous pollutants which has health implications. The introduction of air inlet through the combustion chamber is such that enhances heat retention and reduces heat loss when cooking. In summary, this design is able to achieve 55.4% thermal efficiency and 53.8% heat utilization which is an improvement on 17.9% for traditional three-stone stove as reported by George (1997). Nonetheless, this design fits perfectly for purpose in terms of its reduced size and ease of movement when compared to the wood stove design by Ayo (2009). Again, this biomass stove is a suitable alternative to the conventional kerosene stove with an advantage of cooking with diverse biomass fuel stocks other than fuel wood. More importantly, this stove is a logical next-step towards mitigating the prevailing energy crisis associated with fossil fuels and depleting forest reserves resulting from fuel wood dependence.

5. CONFLICT OF INTEREST

There is no conflict of interest associated with this work.

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