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Fabrication of Improved Biomass Stove from Local Ceramic Raw Materials in South Eastern Nigeria.

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Abstract - A hemispherical ceramic lining was fabricated using 70 wt% Enugu fireclay, 20 wt% Unwana beach sand, 5 wt% sodium feldspar and 5 wt% grog. The ceramic lining was used to line the internal walls of metal biomass cook stove. The water boiling test was used to compare the performance characteristics of the ceramic lined biomass stove and traditional metal biomass stove that has no ceramic lining, using charcoal as fuel. The firepower generated by the ceramic lined stove were 5040.5 watts, 5558.3 watts, and 1375 watts, for the high power (cold start), high power (hot start) and low power (simmering) test phases. The corresponding values of firepower using the traditional metal stove were 4081.5 watts, 5236.1 watts and 1589.6 watts respectively. Efficiency of the ceramic lined stove were recorded as 16 %, 19.8 %, and 46.5 % for the high power (cold start), high power (hot start) and low power (simmering) test phases respectively. The corresponding values of efficiency for the traditional metal stove were 15 %, 17.6 %, and 23.5 % respectively, for the three test phases. These results suggest that the ceramic lining improved the performance characteristics of the ceramic lined stove, by reducing the amount of heat lost to the atmosphere and reducing fuel consumption per meal. It is recommended to use light gauge metal sheets for the fabrication of the encasement of ceramic lined stoves, to compensate for the weight of the ceramic lining. It is also recommended to incorporate an adjustable air draft control at the base of such improved stoves, to control the combustion rate of the biomass fuel.

Keywords: Ceramic, refractory, cook stove, biomass, firepower, efficiency.

1.0 Introduction

Archeological evidence shows that cooking may have started at least since a million years ago, (Rupp 2015). Re–analysis of burnt bone fragments and plant ashes from the Wonderwerk cave in South Africa, has provided evidence supporting control of fire by early humans there, by about one million years ago, (Pringle etal 2012). Archeological evidence from 300,000 years ago, in the form of ancient hearts, earth ovens, burnt animal bones and flint are found across Europe and the Middle East, (Roff 2014).

Early cooking methods include the use of hearts, earth ovens, sun and wind drying and open fire cooking, (Benke 2017). Open fire cooking includes boiling, frying, simmering, stewing, grilling, etc. Most of these open fire cooking methods endure till present day. The common fuels used for open fire cooking include traditional biomass fuels like wood, charcoal, animal dung, crop residue, as well as more modern fuels like kerosene, liquefied petroleum gas (LPG), propane, natural gas, etc.

Traditional fuels often have low thermal efficiency, (Ahmad 2014). A substantial amount of fuel carbon is lost due to incomplete combustion, meaning the global warming contribution per meal is high. The use of traditional fuels also leads to deterioration of air quality, negatively impacting the local environment and human health, particularly among women and children due to their exposure and close contact with burning fuels, (Ahmad 2014).

Most biomass stoves used in rural and semi urban households in Nigeria are of simple design, often a tripod made of welded steel or formed from bricks or lumps of wood. Other forms include a metal encasement, (often old pots or basins) which hold the biomass fuel and a wire gauze placed above the metal encasement, upon which the cooking pot is placed.

Such simple designs mean that a large proportion of the heat generated by the burning biomass is lost to the atmosphere. This implies increased quantities of biomass usage per meal. Recent studies on cooking habits in rural communities have focused on developing cooking stoves with improved performance characteristics. It is however important to incorporate at the design stage of improved stoves, tests that can comparatively evaluate the performance characteristics of improved stoves against traditional stoves, (Smith et al 2007).

Common tests used to evaluate the performance of cook stoves include:

- Water boiling tests (WBT)
- Controlled cooking tests (CCT)
- Kitchen performance tests (KPT)
- Stove use monitors, which is currently under development, (Kipruto 2011).

The key parameters that can be investigated by WBT include thermal efficiency, combustion efficiency, fuel consumption, fuel burn rate and time to boil. However, WBT does not reveal the performance of the stoves during real cooking, but rather only provides a rough approximation, (Kipruto 2011)

CCT simulates the actual cooking experience and can provide reliable results with regards to fuel consumption and speed of cooking in the field.

KPT is a field test that evaluates the performance of the stove in real cooking settings. It is useful in evaluating fuel consumption and assessing the impact and effectiveness of cook stove interventions. However it is often expensive, time consuming and labour intensive, (Kipruto 2011).

This research work aims to develop improved biomass stove by reducing the amount of heat lost to the atmosphere, leading to reduction in the mass of fuel used per meal.

2.0 Description of Study Area

The metal encasement of the stove was fabricated in the welding workshop of the department of mechanical engineering of Akanu Ibiam Federal Polytechnic Unwana Afikpo Ebonyi State. The ceramic lining of the stove was designed and fabricated in the ceramic workshop of the department of ceramic and glass technology. The ceramic raw materials were all sourced locally.

3.0 Materials and Methodology

The raw materials used for the fabrication of the ceramic lining include Enugu fireclay, Unwana beach sand, feldspar and grog. The raw materials were separately milled in a laboratory ball mill, each for about eight hours and afterwards sieved with a 100 mesh sieve to remove oversized particles.

A refractory body was composed by mixing 70% of Enugu fireclay, 20% Unwana beach sand, 5% sodium feldspar and 5% grog. Suitable amount of water was added slowly as the mixture was worked into a consistent plastic mass.

A hemispherical model was made out of a disused aluminium dish. The model was covered with a nylon bag and the plastic refractory body was hand thrown on the model to take the hemispherical shape of the model, with a suitable and consistent thickness. After the shaping operation, the piece was left to dry in open air overnight. The model was later removed gently, followed by the nylon cover.

While the ware was still in the leather hard state, about 20 holes of 2mm diameter were perforated at the base of the lining, for easy disposal of residual ash. The lining was then allowed to dry in open air for six more days before being dried in an electric oven at 110^{o}C for six hours. Afterwards, the lining was fired in a gas kiln up to 1200^{o}C. After cooling and inspection, the ceramic lining was fitted into the metal encasement and a number of tests were carried out on both the ceramic lined stove and traditional metal biomass stove, to evaluate their performance characteristics.

The water boiling test was used to compare the efficiency of the ceramic lined stove against traditional metal biomass stove, as described by Smith et al (2007). The test consists of three phases:

1. Cold Start (high power): Using a cold stove and a cold pot, 2.5 liters of water at room temperature was brought to a boil. This simulates rapid cooking tasks like making tea, boiling milk etc.
2. Hot Start (high power): Immediately following the cold start, the water is replaced with a new batch of 2.5 liters of water at room temperature and brought to a boil.

3. Simmer (low power): Immediately following the hot start, the already boiled water is maintained at a simmer for 45 minutes. In this phase, the stove, pot and water remain hot from the second phase of the test. This simulates slow cooking tasks like cooking rice, beans or hard grains.

For any phase of the test, firepower is the energy released by the burning fuel per unit time. Firepower can be calculated as

$$P_{(w)} = \frac{\left(M_i - M_f\right) x\, H_c}{t} \ldots\ldots.. equation\ 1$$

where

P = fire power in watts (w)

M_i = initial mass of charcoal in the stove (g)

M_f = final mass of charcoal in the stove (g)

H_c = energy content of charcoal (29000J/g) i.e energy contained per unit mass of charcoal

t = time spent during the test phase in seconds (s), (Smith et al 2007).

Efficiency is the ratio of the energy absorbed by the water in the cook pot to energy released by the burning of fuel. For the high power phase, energy absorbed by the water is given by the energy required to raise the temperature of the water to boiling and for the low power (simmering) phase, energy absorbed by the water is given by the energy required to evaporate the water.

Thus for the high power phase,

$$Efficiency = \frac{M_w\, x\, C_w\, x\, \left(T_f - T_i\right)}{\left(M_i - M_f\right) x\, H_c} \ldots\ldots\ldots \text{equation 2}$$

and for the low power phase,

$$Efficiency = \frac{H_w\, x\, \left(M_{wi} - M_{wf}\right)}{\left(M_i - M_f\right) x\, H_c} \ldots\ldots\ldots. equation\ 3$$

Where M_w = average mass of water in the cook pot from pre start to first boiling,

M_{wi} = mass of water at first boiling for the low power (simmering) mode

M_{wf} = final mass of water after test for the low power (simmering) mode

C_w = heat capacity of water (4.184J/g^{o}C)

T_f = temperature at first boiling (^{o}C)

T_i = initial temperature of water in the pot (^{o}C)

H_w = heat of vaporization of water (2260J/g), Smith et al (2007).

4.0 Results and Discussion

Table 1. Calculated values of firepower P(w), for the various test modes using traditional metal biomass stove.

Parameter	High power (cold start)	High power (hot start)	Low power (simmering)
M_i	500 g	342 g	210 g
M_f	348 g	212 g	62 g
t	18 minutes	12 minutes	45 minutes
H_c	29000J/g	29000J/g	29000J/g
P(w)	4081.5 watts	5236.1 watts	1589.6 watts

Table 2. Calculated values of efficiency for the various test modes using traditional metal biomass stove.

Parameter	High power (cold start)	High power (hot start)	Low power (simmering)
M_w	2392 g	2392 g	-
T_i	33 ^oC	33 ^oC	-
Tf	99oC	99.4oC	
M_i	500 g	342 g	210 g
M_f	348 g	212 g	62 g
H_c	29000 J/g	29000 J/g	29000 J/g
C_w	4.184 J/g^{o}C	4.184 J/g^{o}C	-
H_w	-	-	2260 J/g
M_{wi}	-	-	2388 g
M_{wf}	-	-	1941.3 g
Efficiency (%)	15%	17.6%	23.5%

Table 3. Calculated values of firepower P(w), for the various test modes using the improved ceramic lined biomass stove.

Parameter	High power (cold start)	High power (hot start)	Low power (simmering)
M_i	500 g	350 g	232 g
M_f	354 g	235 g	104 g
t	14 minutes	10 minutes	45 minutes
H_c	29000 J/g	29000 J/g	29000 J/g
P(w)	5040.5 w	5558.3 w	1375 w

Table 4. Calculated values of efficiency for the various test modes using the improved ceramic lined biomass stove.

Parameter	High power (cold start)	High power (hot start)	Low power (simmering)
M_w	2392 g	2392 g	-
Ti	32 ^oC	33 ^oC	-
T_f	98.9 ^oC	98.9 ^oC	-
M_i	500 g	350 g	232 g
M_f	354 g	235 g	104 g
H_c	29000 J/g	29000 J/g	29000 J/g
H_w	-	-	2260 J/g
C_w	4.184 J/g^{o}C	4.184 J/g^{o}C	4.184 J/g^{o}C
M_{wi}	-	-	2386 g
M_{wf}	-	-	1622.5 g
Efficiency (%)	16%	19.8%	46.5%

Table 5. Comparison of firepower for the two stove types.

Stove type	High power (cold start)	High power (hot start)	Low power

			(simmering)
Traditional metal biomass stove	4081.5 watts	5236.1 watts	1589.6 watts
Improved ceramic lined biomass stove	5040.5 watts	5558.3 watts	1375 watts

Table 6. Comparison of efficiency for the two stove types.

Stove type	High power (cold start)	High power (hot start)	Low power (simmering)
Traditional metal biomass stove	15%	17.6%	23.5%
Improved ceramic lined biomass stove	16%	19.8%	46.5%

From tables 5 and 6 above, it can be seen that the improved ceramic lined stove has superior firepower values for both the cold start and hot start high power test modes, resulting in higher efficiency values of 16% (cold start) and 19.8% (hot start), compared to 15% (cold start) and 17.6% (hot start), for the traditional metal biomass stove. Similarly, the improved ceramic lined stove has a faster time to boil, 14 minutes (cold start) and 10 minutes (hot start), compared to 18 minutes (cold start) and 12 minutes (hot start), for the traditional metal stove.

Perhaps the clearest indication of the superior performance of the ceramic lined stove can be observed in the efficiency for the low power (simmering) test phase. The ceramic lined stove has an efficiency of 46.5% for this test phase, compared to 23.5% for the traditional metal stove. This implies that far less power is required to maintain simmering, using the ceramic lined stove. This is due to the heat insulation provided by the ceramic lining, limiting the amount of heat lost to the atmosphere.

For most practical cooking situations, more time is spent in the simmering phase than in raising the water to a boil, implying that the ceramic lined stove would require a smaller amount of charcoal to accomplish the entire cooking task, compared to the traditional metal stove.

5.0 Conclusion and Recommendations

From the results discussed above, it can be concluded that incorporating a ceramic lining into biomass stove designs, would limit the amount of heat lost to the environment and improve the overall efficiency of the biomass stove.

It is recommended to use light gauge metal sheets for the fabrication of the outer encasement of the ceramic lined stove, to reduce the overall weight of the stove.

It is also recommended to incorporate a manually adjustable air draft control at the base of the improved biomass stove, to control the combustion rate of the biomass fuel. This would likely further improve the overall efficiency of the stove.

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Fig. 1. The improved ceramic lined biomass stove assembly.

Fig. 2. The perforated ceramic lining of the improved biomass stove.