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Development of a Rocket Stove Using Woodash as Insulator

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Abstract

A rocket stove which serves as a cheaper and more safer alternative to conventional method of cooking, employing the use of solid fuels has been developed. The construction was done with our locally available metallic materials for the body and combustion chamber of the stove, using teak (khaya grandifoliala) wood ash as an insulator. An analysis of the thermal and mechanical properties of the insulating wall, fuel magazine, combustion chamber, and chimney were also performed; the law of energy conservation was used to determine the stove thermal efficiency which is 37.3%, while the Newton's law of cooling was used to determine the convection heat transferred by the stove body (150864 J/kg) and Stefan-Boltzmann law was used to determine the amount of heat radiated by the stove body (49.2 J/kg), thus, signifying its suitability for home heating. A less expensive but very effective materials mixture containing galvanized steel and wood ash were found to have thermal properties comparable to that of fired vermiculite and stainless steel materials which are more expensive in other improved stove designs.

Keywords: Rocket stove, Solid fuels, Insulator, Convection, Radiation, Wood Ash

1.1 Introduction

In the developing countries including Nigeria, most of the population living in the rural areas depends on biomass fuels especially wood, cow dung, charcoal, etc., for cooking purposes (Ahmad et al.: 2014). Often, the combustion of these fuels is done indoors over open fires with little or no means of ventilation. Extended exposure to biomass emissions significantly increases the risk of acute respiratory infections, chronic bronchitis, and obstructive pulmonary disease (Bruce, PerezPadilla et al. 2002). Approximately half a million premature deaths and nearly 500 million cases of illness are estimated to occur annually as a result of exposure to smoke and harmful emission coming from biomass combustion. As per world health organization report, indoor air pollution is the third leading health risk affecting the people directly and indirectly especially women and female children in the rural areas and around the globe (WHO, 2006).
It is estimated that 56% of this total are children under the age of five (Warwick & Doig, 2004).

Awareness of the environmental and social cost of using traditional fuels and stoves has grown. At the same time, studies of the problem have resulted in proven strategies to reduce both fuel use and harmful emissions. Unfortunately, the local stove currently available do not always represent the best designs that modern engineering can offer. The Partnership for Clean Indoor Air was launched by the U.S Environmental Protection Agency (EPA) and other leading partners at the World Summit for Sustainable Development in Johannesburg in September 2002 to improve health, livelihood and quality of life by reducing exposure to indoor air pollution primarily among women and children, from house hold energy use. Over 80 organizations are working together to increase the use of clean, reliable, affordable, efficient and safe home cooking and heating practices that reduce people's exposure to indoor air pollution in developing countries (Bailis et al 2007). Extended exposure to biomass emission significantly increases the risk of acute respiratory infections, chronic bronchitis, and o bstructive pulmonary disease (Bruce, Perez-Padilla et al. 2002).

Research, design and development of improved biomass stoves have been undertaken in some African countries and beyond (Dana: 2009; Mande 2009). These has resulted in many stove design dedicated to a particular fuel and a particular application. A stove designed for a particular fuel and a particular application can be used for different fuels and applications but may not perform with the same effectiveness (Dana: 2009). Stove dissemination programs have been met with varying levels of success. As is true with any development initiative, the sustainability of an improved stove is project is not driven by the technology alone. Social, cultural, and economic factors have a significant effect on the stove use and adoption rates (Shama et al). The most successful stoves are easy to construct in local settings using existing techniques and materials and have clear advantages with respect to fuel economy, ease of use, durability and cleanliness (Schreiner: 2011).

Modern cooking stoves are designed to clean up combustion first. Then the hot gases can be forced to contact the pot increasing the efficiency with other many advantages. Stoves do more than save wood and reduce smoke (Baldwin: 1987). How the stove cooks food is usually the most important to the users. Good and improved stove can make cooking with fire easier, safer, and faster and can add beauty to the kitchen (Tiyagi et al: 2013). It is quicker to start, needs little tending and can meet specific needs of a cook, and therefore, a successful design is appreciated as an addition to the quality of life.

Energy is important for improving the quality of life, public facility and economic growth. Access to modern sources of energy needed for every developed country to support its development (Yuntenwi et al., 2008). In developing countries, access to affordable and reliable energy services is fundamental to reducing poverty and improving health, increasing productivity, enhancing competitiveness and promoting economic growth (Ahmad et al. 2014).

What triggered this study is the perceived need for improved cooking stoves most especially in the rural community where their major source of cooking fuels are wood, charcoal, rice dusk etc,. The newly improved cooking stoves are based on better design principles; they have the better combustion efficiency and thus reduce the fuel consumption to a greater extent (Yuntenwi et al., 2008). The bases of this project,the design and construction of a rocket stove, is to improve and modify the modern cooking stoves which principles were described by Winiarski who studied combustion and wood burning cooking stoves for more than 30 years (Still et al, 2015). The rocket stove is designed to increase fuel efficiency with regards to its thermal efficiency, a combination of enhanced combustion efficiency and heat transfer associated with the combustion of wood fuel.

2.0 Material and methods

An industrial survey was conducted at a Rocket Stove Manufacturing Site owned by the International Center for Environmental Development (ICEED),Ndibe Beach Road Afikpo in Ebonyi State, where relevant information that aided the stove construction were obtained. For the purpose of having a greater understanding of cooking practices using the 60 liters capacity stove and to evaluate the performance of the rocket stove, users' survey was also conducted at Sir Francis Ibiam Grammar school, a female boarding house secondary school in Afikpo, Ebonyi State. The chief cook and other cooks were interviewed on the stove performance, efficiency, reliability, and the method of cleaning.

Design Considerations: During the design, several important stove design parameters were varied for efficiency and comparison. First, the stove inlet cross sectional area was an important factor which determines the amount of wood feed into the stove. Secondly, the chimney height has a serious impact on the heat radiation from the flame to the pot. Thirdly, the gap between the top of the stove and the bottom of the pot influences how much heat from the flue gases and flames that are transferred to the pot. Fourthly, the amount of insulation in the stove influences how long it will take the stove to be heated up and thus affecting the efficiency. Finally, usage of a skirt around the pot increases heat transfer around the perimeter of the pot. These factors were varied from a baseline setup to examine their effect on the stove performance.

Materials Selection: In selecting materials for the construction of the stove, the recommended materialsby ICEED were considered and evaluated with regards of the following properties: weldability, machineability, durability, heat conductivity, toxicity, weight, availability and cost effectiveness as shown in Table 1 and Table 2.

Table 1: Comparative Materials Property Table for Ceramics, Earthen Materials, Aluminum, Mild Steel, Galvanized steel and Stainless steel

S/N	Design objectives/ material	Ceramics material	Aluminum material	Earthen material	Mild steel material	Galvanized steel material	Stainless steel material

1	Weldability	P	G	P	E	G	G
2	Availability	F	F	E	E	G	P
3	Machinability	P	G	P	F	F	P
4	Durability	G	E	F	G	E	E
5	Cost effectiveness	P	G	E	E	G	P

Table 2: Comparative Materials Property Table for Vermiculite, Dry Wood Ash, Pumice Rock and Aluminum Foil

S/N	Insulating materials/ Design objective	Vermiculite	Pumice rock	Dry wood ash	Aluminum foil
1	Availability	P	F	E	G
2	Durability	E	G	G	G
3	Cost effectiveness	P	P	E	F
4	Non-toxic	G	E	E	E
5	Weight	E	P	F	E

KEY: E=Excellent, G=Good, F=Fair, P=Poor.

From tables I and 2, the following materials were chosen: *Mild Steel Material* By the above criterion and recommendation from literatures, the mild steel material is suitable for constructing the stove body and the pot skirt. It is cost effective, has excellent weld-ability, it is readily available, and due to its ductile nature it is easily formed into shapes. *Galvanized Steel Material*: The galvanized steel is used in place of stainless because of its cost effectiveness. It also has high corrosion resistance, good weld-ability, excellent durability and readily available. Hence, these properties make it suitable for constructing the combustion chamber, chimney, and fuel magazine. *Dry Wood Ash from* teak (*khaya grandifoliala*) *wood:* The dry wood ash is the most available among other insulating materials listed above. For the purpose of this research, teak (*khaya grandifoliala*) wood ash was used. It has considerable weight, excellent durability, and it is very cheap to get may be free. Hence, it was adopted.

Method of Performance Test

The Experimental Procedure for Testing the Stove Performance is as follows;

- ✓ The stove and pot were thoroughly cleaned and dried before commencing the test.
- ✓ 250grams of wood was weighed with a balance and the mass was recorded.
- ✓ The empty cooking pot was weighed with its lid, and the mass was recorded.
- ✓ The cooking pot was weighed with water and the mass was also recorded.
- ✓ The initial water temperature was measured using a glass thermometer and the thermometer reading was taken.
- ✓ The room temperature was also measured and the temperature was recorded.
- ✓ The already weighed wood was arranged into the fuel magazine and a drop of kindling fuel was sprayed, then the stove was lighted.
- ✓ The cooking pot with water was placed on the fire and the stop watch was started.
- ✓ The temperature of the water was recorded at intervals of 5mins until the water was observed to be vigorously boiling.
- ✓ The cooking pot was put down as soon as the water boiled and the temperature was checked, the reading was recorded in the data sheet.
- ✓ The time taken for water to boil was recorded and the fire was put off and the
- ✓ remaining charcoal was collected with a tong and tray.
- ✓ The remaining charcoal was weighed and the mass recorded in a data sheet.

The industrial survey carried out on the stove design gave the following insight to the component sizing and method of construction, which are presented in Table 3 and Table 4 respectively.

Table 3: Industrial Survey Questions and Responses

S/N	Industrial Survey questions	Responses
1	How can the stove capacity be determined?	The diameter and height of the stove and pot are used.

2	What is the appropriate size for combustion chamber?	The appropriate size is dependent on the pot diameter.
3	What determines the height of the stove chimney?	The size of the combustion chamber.
4	What determines the size of the pot skirt?	The size of the pot that should be used on the stove.
5	What are the insulating materials that can be used in a stove construction?	Vermiculite, pumice rock, dry wood ash and fiber glass.
6	What are the methods that can be used in a stove construction?	Welding, folding, fastening, and molding.
7	What are the materials that can be used in a stove construction?	Metals, Ceramics, and earthen materials.

Preliminary Stove Design Parameters

In improved stove construction proper gaps are extremely important, if the gaps are too small the stove will not burn properly and smoke may back out the fuel magazine. Similarly, if the gaps are too large, the heat will not be transferred to the pot but will escape through the exhaust. Hence this prototype gaps and dimensions were modeled as follows:

Let: D_p = pot diameter, d = diameter of stove, J = height of combustion chamber, H_c = height of chimney from the floor, K = height of the chimney from the top of the fuel magazine, A_j = area of the combustion chamber and L = Length of the fuel magazine.

Rocket stove design principles of Winiarski was adopted (Dana: 2009). Thus, the formula's for determining the above parameters are:

$K = 1.5J$

$H_c = K + J$

$A_j = J \times J$

$L = 1/2d + 10$

To determine the volume of the stove body and the capacity of the pot skirt, since they are both cylindrical in shape:

Using; Volume $V = \Pi r^2 h$

Where; r = radius, h = height o f the cylinder, Π = constant (22/7)

Table 4: Preliminary Stove Design Parameters

Table 5: Test Result for the Water Boiling Test

S/N	Initial Temp. of Water T_1	Final Temp. of Water T_2	Mass of Water m_w (g)	Mass of Fuel m_f (g)	Mass of Pot m_p (g)	Mass of Charcoal m_c(g)
1	28^0C	95^0C	355	250	795	5

There are relation between combustion temperature dynamics and combustion time. The higher the combustion temperature the faster combustion time and vice versa. This is clearly seen in Figure 2 such that at when the Temperature increases to (100°C) the combustion time also increases to 12.5mins.

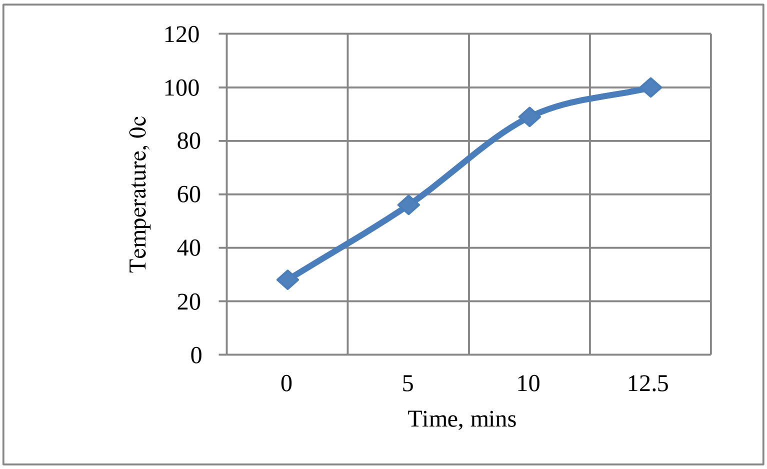


Figure 2: Time – Temperature Variation during Boiling.

Designs for Optimal Insulation Thickness

Q_{in} = Rate of heat transfer when insulation is added [16]

$$= \frac{2\pi L\,(T_1 - T_2)}{\dfrac{\mathrm{In}\left(\frac{r_1}{r_2}\right)}{\mathrm{Kmildsteel}} + \dfrac{\mathrm{In}\left(\frac{ti}{r2} + \frac{r2}{r2}\right)}{Kinsulator}} \qquad (1)$$

Where; L = Length of cylinder section

T_1 = Inner temperature of rocket stove T_2 = Outer temperature of rocket stove $t_{i(opt)}$ = Optimal insulation thickness r_1 = Radius of the inner cylinder section r_2 = Radius of the outer cylinder section $k_{mildsteel}$= Thermal conductivity of mild steel (43 W/m^0c) $k_{insulator}$ = Thermal conductivity of wood ash ($0.02W/m^0c$)

Thermodynamics Modeling Analysis

Fundamental theory of heat and mass transfer and law of conservation of energy were applied in this analysis. Using the law of conservation of energy which states that energy can neither be created nor destroyed (Rajput, 2010)];

$Energy_{input}$ - $Energy_{output}$ = Energy change (2)

For the stove, the energy input is based on the energy stored in the wood fuel according to the following equations:

$E_{input} = M_f L_f - M_c H_c$ (3)

Where; M_f = mass of wood

L_f = lower heat value of wood (17500kj/kg)

M_c = mass of remaining charcoal

H_c= higher heat value of charcoal (34100kj/kg)

The energy output is based on the energy transferred to the water, it is modeled by:

$E_{output} = M_w C_p \Delta T + M_e L$ (4)

Where; M_w = initial mass of water

C_p = specific heat capacity of water (4185j/kgK)

ΔT = change in the water temperature from initial to boiling

M_e = mass of water evaporated

L = latent heat of vaporization of water (2260kj/kg)

In this model, conduction losses are negligible as they are accounted for in the change of energy of the stove. Convection and radiation losses may be calculated for both the stove and the pot based on their surface temperature during combustion.

Convection is modeled by Newton's law of cooling:

$q = hA(T_s - T_\infty)$ (5) Where;

q = heat transfer

h = convention heat transfer coefficient ($20W/m^2$)

A = surface area

T_s = surface temperature

T_∞ = ambient fluid (air) temperature Radiation is modeled by the Stefan-Boltzmann law:

$$q = \varepsilon\sigma T_s^4 - \alpha\sigma T_\infty^4 \quad (6)$$

Where; q = heat transfer

ε = emissivity

σ = Stefan- Boltzmann constant

α = absortivity

T_∞^4 = ambient fluid (air) temperature

T_s^4 = surface temperature

Since no energy is created or destroyed in within the control volume of the stove and the pot, the change in energy term is based only on the energy stored within the mass of the stove and pot. The energy storage term are based on the specific heat of the materials according to the following equations: (Durowade, 2009).

$$\Delta E = m\, C_p\, \Delta T \quad (7)$$

Where: m = mass

C_p =specific heat

ΔT = change in temperature

Therefore the fundamental theories of heat transfer are combined with the law of conservation of energy in order to determine the magnitude and location of the heat losses from the stove. Using the following equations Tukana, 1993).

$$E_{input} - E_{output} = E_{stove\ con.} + E_{stove\ rad.} + E_{pot\ con.} + E_{pot\ rad.} + \Delta E_{stove} + \Delta E_{pot} + \Delta E_{dif}. \quad (8)$$

Finally, efficiency (η) is calculated from the simple equation of output ratio input:

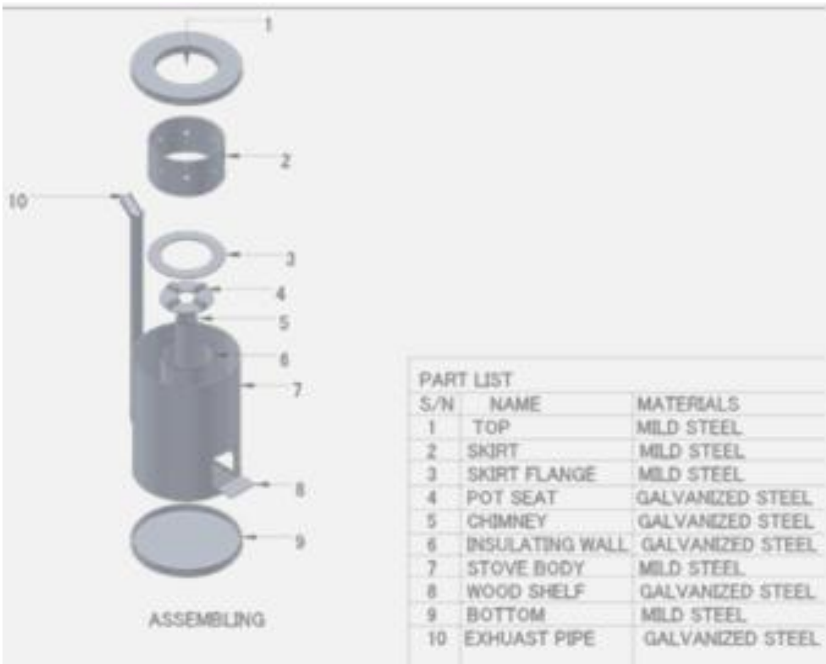
$$\eta = E_{output} / E_{input} \quad (9)$$

Table 5: Thermodynamics Analysis Result Values

S/N	Parameters	Values	Units
1	Energy input	2670	Joules
2	Energy output	99540.2	Joules
3	Heat transferred by convection	150864	J/kg
4	Heat transferred by radiation	49.2	J/kg
5	Optimal insulation thickness	7364.2221	Watt
6	Efficiency	37.30%	

The results show that the rocket stove has a maximum thermal efficiency of 37.3% and energy input and output of 2670kJ/kg and 99540.2kJ/kg respectively. This represents an improved thermal efficiency compared to the kerosene stove which has a lower average thermal efficiency from literature. The improvement in performance can be linked to a number of factors. The first is the incorporated blower which supplies secondary air for combustion, thereby enabling a very high combustion of the fuel. Secondly, the reduced height of the chimney shortens the distance travel by the heat from the combustion chamber to the pot base. And lastly, is the use of an efficient lagging material (dry-wood ash), to prevent heat loss from the stove inner and outer walls. Thermal efficiency indicates how effective heat energy from the fire is transferred to the cooking pot; high thermal efficiency may also coincide with the production of excess steam. Energy carried away by steam cannot be utilized in the cooking process (Dhillon & vonWuehlisch, 2013; Performance Estimation of Stoves: 2013).

From the result above, as detailed in the data tables; it shows that the heat losses by convection is $151.2w/m^2$ and the heat losses by radiation is 2.57×10^{-8}. The normal stove temperature as recorded during the experiment makes it clear that the materials used in the construction is of high thermal conductivity and of high specific heat capacity. Heat losses in different forms from different areas of the stove; with proper minimization of this heat loss, it will bring about maximization of the amount of heat transferred to the water. On the average for all stove tests, convention accounts for 77%, radiation accounts for 12% and storage for 11% of total heat loss from the stove. For cooking pot, convention accounts for 92%, radiation accounts for 6% and storage accounts for about 2% due to the mass and temperature of the stove components, these proportions is appropriate. Figure 3, shows the Solid View and Parts List of the developed Rocket Stove.



PART LIST

S/N	NAME	MATERIALS
1	TOP	MILD STEEL
2	SKIRT	MILD STEEL
3	SKIRT FLANGE	MILD STEEL
4	POT SEAT	GALVANIZED STEEL
5	CHIMNEY	GALVANIZED STEEL
6	INSULATING WALL	GALVANIZED STEEL
7	STOVE BODY	MILD STEEL
8	WOOD SHELF	GALVANIZED STEEL
9	BOTTOM	MILD STEEL
10	EXHUAST PIPE	GALVANIZED STEEL

Figure 3: Solid View and Parts List of a Rocket Stove

4.0 Conclusion

An attempt has been made to design, construct and test a rocket stove using wood ash gotten from teak (khaya grandifoliala) as insulator, the test has shown that the construction of a rocket stove using wood ash as insulator perform better and more efficient. From the performance test there is thermal efficiency of 37.3% and energy input and output of 2670kJ/kg and 99540.2kJ/kg was achieved by introducing an air blower which supplies a secondary air into the stove, thereby, aiding the combustion and the thermal efficiency of the stove, making it more user-friendly in terms of health, comfort and convenience. Hence, there is a need to replace the traditional and inefficient cooking devices with efficient cooking devices such as the improved biomass rocket cook stoves in order to increase the use of clean, reliable, affordable, efficient and safe home cooking and heating practices and reduce the sufferings associated to unsafe cooking practices.

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