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# Comparative Studies of Single and Cascaded Rocket Firewood Burning Stoves Based on Energy Analysis Method

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**ABSTRACT - In Nigeria, the total wood removals from forests in 2005 amounted to 86,626,797 m$^3$. The amount of fuel wood consumed from forests in the year 2005 was 72,710,935 m$^3$. As at 2018, emissions from Nigeria's kitchens contributed to about 55 million tons of $CO_2$. A huge amount of these emissions are from large scale cooking in our boarding secondary schools, commercial restaurants and large households. The traditional three stone stoves being used in these quarters are inefficient; hence, the need for developmental research works on Improved Cooking Stoves (ICS). Towards the direction, a lot of ICS have been developed; however, there is still some knowledge gaps that need to be filled in the areas of combustion and thermal efficiencies. This work presents the comparative thermal and exergy efficiency analysis single and cascaded three pot firewood energy saving stoves. The 50cm diameter pot stoves were constructed using 2mm thick steel metal with inner linings filled with ash as insulating material. The cook stoves were tested using standard water boiling and cooking test methods. It was shown from the analaysis of the result that; the single pot and cascaded-pot rocket stove were estimated to have thermal efficiencies of 28.7, 42.45%, and 43.55%, respectively. The Specific Fuel Consumptions (SFC) for the respective stoves was 0.31, 0.21 and 0.19. The Specific Time Spent (STS) in cooking were 8.43, 6.9 and5.9 respectively. A single-pot and cascaded - pot cook stove can save about 27,231.4 and 40,847.1 toe/ capita of fuel wood per annum, respectively. The result shows that Carbon emissions of single and cascaded cook stove are estimated to be reduced by about 1886kg and1990 kg per annum respectively.**

**Key words: cascaded rocket stove, thermal and exergy efficiencies**

## 1. INTRODUCTION

### 1.1. Background

In 2020, Nigeria has a population of about 206 million people, -3.2% Growth Domestic Product (GDP) growth rate, total consumption/GDP 83.7 and CO2 emissions of 0.43tCO2/capital (www.enerdata.net/estore/energy-market/nigeria/).

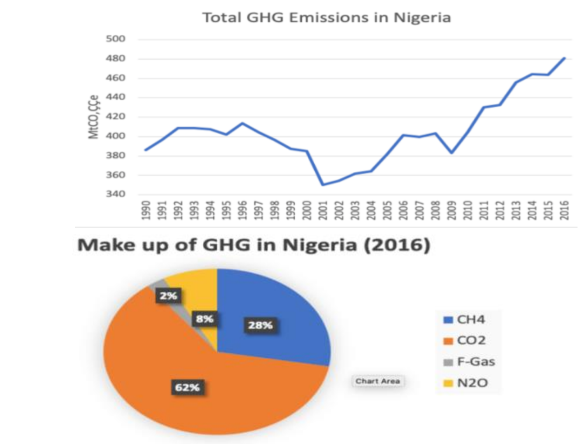


**Figure1: Nigerian Carbon Profile (Source: https://www.carbonbrief.org/the-carbon-brief- profile-nigeria/ )**

This translates to a total emission of 88.58 million tones of CO2. The household cooking sector being the largest consumer of energy in Nigeria, using around 80% of the total, 90% which is derived from biomass, particularly fuel wood (Haruna et al., 2015), accounts for about 63.72 million tones of CO2 emission in Nigeria from burning of fuel wood to meet cooking energy needs.

**Table i: Nigeria Energy Consumption by Source for Cooking Source: Federal Ministry of Environment 2014 brochure on Scaling-up Renewable Energy Development 9n Nigeria, quoted from National Bureau of Statistics**

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| | Primary Energy Supply | Final Con-sumption | Primary Energy Supply | Final Con-sumption | Primary Energy Supply | Final Con-sumption | Primary Energy Supply | Final Con-sumption | Primary Energy Supply | Final Con-sumption |
|---|---|---|---|---|---|---|---|---|---|---|
| **Energy source** | **Nigeria** | | **Bangladesh** | | **Brazil** | | **Indonesia** | | **South Africa** | |
| Coal | 20 | 20 | 912 | 698 | 15,431 | 8,296 | 31,476 | 11214 | 98,477 | 16,676 |
| Crude Oil | 6,012 | 0 | 1,534 | 0 | 97,992 | 0 | 49,807 | 1704 | 20,489 | 0 |
| Oil Products | 6,525 | 10,858 | 3,324 | 3,964 | 11,035 | 1,000,209 | 22,786 | 62720 | 572 | 24,321 |
| Natural Gas | 8,027 | 1,351 | 16,614 | 6,890 | 22,887 | 12,744 | 34,761 | 16650 | 3,794 | 1,631 |
| Nuclear | 0 | 0 | 0 | 0 | 4,081 | 0 | 0 | 0 | 3,519 | 0 |
| Hydro | 486 | 0 | 76 | 0 | 36,837 | 0 | 1,068 | 0 | 177 | 0 |
| Geothermal, solar, etc. | 0 | 0 | 0 | 0 | 653 | 420 | 16,112 | 0 | 82 | 72 |
| Biofuels and Waste | 97,255 | 94,682 | 8,836 | 8,836 | 77,912 | 56,939 | 52,998 | 52266 | 14,526 | 10,638 |
| Electricity | 0 | 2,036 | 0 | 3,194 | 3,086 | 39,280 | 0 | 13749 | -264 | 17,790 |
| **Total** | **118,325** | **108,947** | **31,294** | **23,581** | **270,028** | **217,889** | **209,009** | **158301** | **141,372** | **71,127** |
| **toe per capita** | **0.73** | **0.67** | **0.21** | **0.16** | **1.37** | **1.11** | **0.86** | **0.65** | **2.79** | **1.41** |

The reliance on fuel wood for domestic energy supply has exacerbated deforestation, which is also contributing to desertification in some parts of the country (Haruna *et al*., 2015). The annual deforestation rate is estimated at around 3% per year, which is equivalent to the loss of 410,000 hectares of forested land annually (Haruna *et al*., 2015). Another major concern is indoor air pollution from burning biomass in open fires and usually without chimneys, leading to respiratory diseases and premature deaths (Haruna *et al*., 2015). In a relative study, Babanyara and Saleh (2010) reported that between 1990 and 2000, Nigeria lost an average of 409,700 hectares of her forest which is equal to an average annual deforestation rate of 2.38%; and between 2000 and 2005, it was reported that 35.7% of Nigerian forest cover was lost, amounting to about 6,145,000 hectares of land. They emphasized that the factors causing fuel wood demand in urban areas amongst others include; rural-urban migration, urbanization, poverty, hikes in prices of kerosene and cooking gas (Ajunwa *et al*., 2021). World Health Organization (WHO) estimates 79,000 deaths per year in Nigeria from indoor air pollution, mainly caused by biomass burning (Haruna *et al*., 2015). Haruna *et al*., (2015), asserts that deaths from acute lower respiratory infection in children younger than five years account for about 90% of the total number of deaths from indoor air pollution, while chronic obstructive pulmonary disease in adults of 30 years or over accounts for the remaining 10%. Furthermore, both women and children, particularly in rural areas are usually burden with the rigors of travelling long distances in search of wood for cooking. This results in waste of their productive time and exposure to some vulnerable reptiles.
Although other sources of cooking energy are used in Nigeria, including liquefied petroleum gas (LPG), kerosene, and electricity, they are expensive compared to biomass, which is available at little or no cost (Haruna *et al*., 2015). With over 60% of people earning less than $1 per day (Bello and Roslan, 2010), biomass stands as the preferred source of household cooking energy in Nigeria. Poor assess to electricity and other energy sources are also a major challenge, especially in rural areas. Only about 40% of the population is connected to the national grid (Sambo, 2009; Babatunde and Shuaibu, 2009) with 90% of rural areas having unreliable or no electricity at all (Obadote, 2009). This virtually eliminates electricity as a source of cooking energy for almost half the population (data.worldbank.org/).

Table ii: Nigeria Energy Consumption by Source **(Source: Federal Ministry of Environment 2014 brochure on Scaling-up Renewable Energy Development 9n Nigeria, quoted from National Bureau of Statistic)**

| Source | Percentage |
|---|---|
| Fuel wood | 69.8 |
| Kerosene | 26.6 |
| Gas | 1.11 |
| Charcoal | 0.84 |
| Electricity | 0.52 |
| Crop residues/sawdust | 0.09 |
| Animal waste | 0.07 |
| Others | 0.84 |

## 1.2. Biomass Cooking Stoves

Biomass cook stove is a device developed for burning biomass to release heat energy for cooking. A typical example is as shown in figure 3 below.

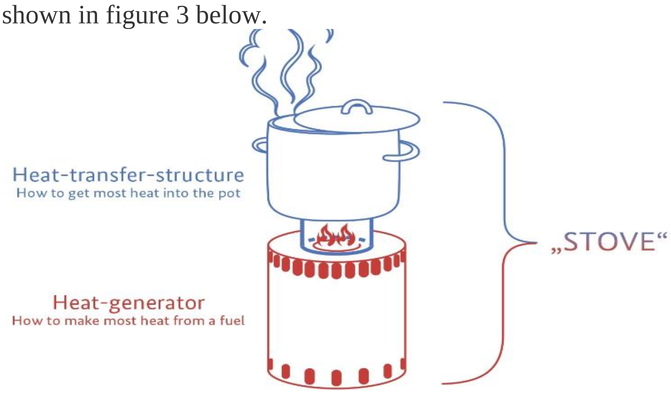


Figure 2: Cooking Stove
Source: https://energypedia.info/wiki/File:Stove_scheme_GIZ_HERA.jpg

Besides cooking, stoves provide useful energy for space/water heating, in-house lighting, fish/meat smoking, and grain/flour roasting (Milind and Vilas, 2014). The same device in many cultures, serves more than one of these functions. Modern cook stoves guarantee more than a plain fire; features such as high efficiency, low emissions, and safety of the user. Biomass Cooking stoves are as old as the human history. They have evolved in numerous shapes and sizes, made up of varied materials, and adapted to different cultures and cuisines, with the advent of time. According to the wide range of food habits, socio-cultural factors, and fuel type available; there exist, number of cook stove designs across the world whether traditional or improved and can be broadly classified in to different categories as shown in figure 3.

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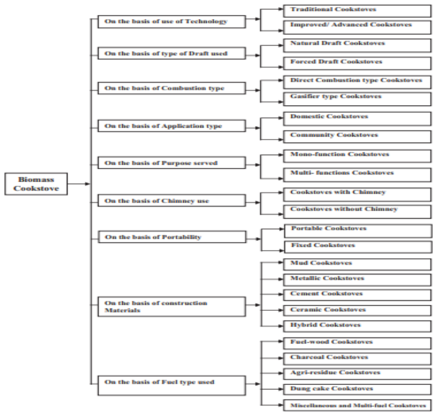


**Figure 3: Classification of Biomass cooking Stoves (Source: Milind and Vilas 2014)**

### 1.2.1. Improved Cooked Stoves (ICS)

One potential solution to this complex set of problems has been identified to be the use of cleaner-burning stoves, known as improved cook stoves (ICSs; Annenberg et al., 2013). The Cook stoves are commonly called "improved" if they are more efficient, emit less emission or are safer than the traditional cook stoves or three-stone-fires. The term usually refers to stoves which are burning firewood, charcoal, agriculture residues or dung. Milind and Vilas (2014) stated that the goal of an ICS design is to improve upon the shortcomings of the traditional stoves, while still ensuring lower cost and ease of use. A few common design strategies are placing a fuel-grate under the burning fuel, provision of low density and specific heat walls for enclosing fire, provision of a short internal chimney above the fire, designing properly sized channels for forcing heat into the pot, and use of insulation (Milind and Vilas, 2014)..

A diverse set of interests have coalesced into a global community that is motivated toward dissemination of ICSs (Simon, Bailis, Baumgartner, Hyman, & Laurent, 2014). There is limited empirical evidence, however, of programs that have achieved the desired behavior change — ICS adoption and use—let alone the environmental and health benefits of ICSs (e.g., Hanna et al., 2012; Lewis & Pattanayak, 2012).

Several investigative studies have been carried out on energy analysis and improvement of woody biomass, herbaceous and agricultural biomass. Baldwin (1987) studied the performance of traditional three stone open - fire stoves and reported that; only 8% of the heat energy is absorbed by the water or food, 10% is lost by evaporation from the pot and 82% is lost to the environment. This results in the underutilization of fuel wood, and a consequent increase risk of deforestation. Kammen and Fayemi (1992) reported on the Kenya Ceramic Jiko (KCJ) stove to have a useful heat of about 25-40 % of the heat generated compare with an open fire which they reported directed just 5-10% of the heat generated to the cooking pot. This is also supported by the findings of Ballard Tremeer and Jawurek (1996) who compared five rural wood-burning cooking devices including those of the open fire, improved open fire, one pot metal stove, two-pot ceramic stove and two pot metal stove; and reported a mean efficiency of 14% for the traditional open fire, 21% for the improved open fire, 20 to 24% for the rest of the stoves with no significant difference (at 90% confidence) between them. In many works, the findings have consistently showed the performance of the improved stove over the three-stone stove. Okafor and Unachukwu (2012) who compared the performance of a three-stone stove and that of an improved nozzle-like cook stove, also reported an increased thermal efficiency of the nozzle-like stove over to the open fire. Reports have also shown that skirts improve the thermal efficiencies of wood stoves when used on them. Thacker et al. (2017) for instance stated that the traditional channel cook stove have a very low heat transfer efficiency; pot skirts were reported to be one of the most effective ways to improve this deficit. They also stressed the importance of increased heat transfer efficiency to be decrease in cooking time and smoke reduction. In his work, Zube (2010) reported that pot skirts functions by directing the hot gases to pass directly along the sides of the pot, resulting in higher flow temperatures and higher heat transfer efficiencies. Concerning skirt, Wohlgemuth et al. (2009) also reported that pot skirts normally absorb some of the convective heat released by the gases and re-radiates it back to the combustion zone to promote more efficient combustion. For instance, the work carried out in Dadaab Refugee Camps, Kenya, and reported by Pennise et al. (2010) on the performance of two stoves: the StoveTec and Envirofit stoves fitted with skirts showed a 30 % increase in fuel and thermal efficiency in the laboratory water boiling tests carried out on the stoves. Adkins et al. (2010) also tested the performance of three stoves; the Ugastove fitted with a skirt, the StoveTec and the Three Stone stove. He equally reported that the Ugastove stove showed a fuel wood savings of 46%, and the Stove Tec showed fuel wood savings of 38 % when compared with the three stone stove. He also measured the cooking time and reported that the three-stone fire required approximately 17 min to cook. The Ugastove showed an increase in cooking time of 27% over the three-stone fire, whereas the Stove Tec stove showed only a slight increase of 5% in cooking time. Andreatta (2007) further proved the importance of a skirt in an experiment in which he carried out to determine the effect of skirt by using two pots. He skirted one of the pots and left the other. With the pot skirt present, he discovered that the heat transfer was 1465 W and 1107 W without the skirt. The effect of skirt was also reported by Wohlgemuth et al. (2009) who conducted experiments both with and without the pot skirt. With the use of the skirt, they reported an optimum increase in the thermal efficiency from 20.7% to 28.7%. Thacker et al., (2017) incorporated a set of pot skirts to a traditional stove and compared its performance with when skirts were not used on the stove. For the laboratory test using the Water boiling test (WBT), they reported a 41.7% increase in thermal efficiency, 32.7% decrease in fuel consumption and 28.8% decrease in cooking time with the use of the skirts. Bhattacharya and Salam (2006) reported a stove called the Rocket Stove developed at Aprovecho Research Center, USA, in the early 1980s. They included the use of a metal skirt around the pot in order to improve contact of the vertical surface of the pot with the rising flue gas, etc. The efficiency of a Rocket Stove with skirt was reported to be 36% efficient. The Aprovecho Research Centre in USA and Shengzhou Stove Manufacturer (SSM) in China (2009) also designed and manufactured a rocket stove whose combustion chamber is made from local clay mixed with sawdust and fired to produce an insulating material. The laboratory and field tests of the stove with skirt showed a saving of 50% of fuel wood; 50 to 70% of particulate emissions; and 50 to 60% of carbon monoxide emissions, compared to Three-Stone Fire. This work presents the effect of using skirt on the thermal efficiency and specific fuel consumption of a designed and fabricated stove using the Winiarski design concept as reported by Bryden et al. (2005). Ajunwa et al (2021) developed and tested a wood stove without a skirt and with a detachable skirt of height 120 mm (same height as the pot used for the experiment) to determine the influence of the skirt on the stove in terms of thermal performance in a water boiling test. The evaluation of thermal efficiency and specific fuel consumption showed that; the stove tested without a skirt gave an average thermal efficiency of 31.33% and an average specific fuel consumption of 0.14 kg/l., whereas the one tested with a skirt, however, gave an average thermal efficiency of 38.65% and an average specific fuel consumption of 0.09 kg/l. This signifies an improvement in thermal performance by the use of skirt on the stove designed.

### 1.2.2. Advanced Biomass Stoves.

Advanced biomass stoves (ABS) are recently developed, factory-manufactured cook stoves, based on modern technical and product development research; and standards that include higher efficiency, lower emissions, better safety and enhanced durability (Venkataraman et al., 2010 and world bank, 2010). These next-generation cook stoves commonly have advanced features, such as induced or forced airflow for cleaner burning. ABS, enables factory-based production, undergoes thorough quality testing, and hence increases the possibility of accurate reproduction of the design in all the stoves. Although current ABS shows significant emissions reductions over traditional stoves, LPG-like emission levels are yet to reach [22]. Currently, there are two broad categories of ABSs available, Gasifier stoves with two-stage combustion and the improved "Rocket" stoves with one-stage combustion. An example of "Rocket" stove type ABS are "Envirofit International's Family of Rocket Stoves" claiming to reduce fuel use by 60%, CO emissions by 60%, and black carbon by 40%. Another example is the 'StoveTec' from ARC which claims to use 40–50% less fuel, about half the cooking time, and emitting 50–75% less smoke as compared to TSF (World bank ,2010).

Prasad et al, (1981) and Samuel (1987) performed many heat-transfer studies and identified number of variables for designing stove using engineering approach. Important variables are grate area, the shape of the combustion chamber; its diameter, height and volume; bulk flow rate, temperature distribution, excess air ratio, primary to secondary air ratio, fuel dimensions and moisture content, fuel bed height and porosity, effect of the skirt and the firepower. In Nigeria, advanced cook stoves are being developed and deployed, though currently on a small-scale. For example, the German organisation Atmosfair has, thus far, distributed over 10,000 advanced stoves and the American C-Quest Capital has deployed around 6500 units, with the plans to increase distribution to 1.2 million over the next decade (http://cleancookstoves.org/resources).

Between 2015 and 2019, the centre for renewable energy research, Umaru Musa Yar'adua University Katsina, through an European Union Project on Agro forestation and improved wood burning stoves in collaboration with Katsina State Government and International Fund for Agricultural Development, developed and disseminated over 50,000 efficient fire wood burning stoves to Katsina, Zamfara, Jigawa, Sokoto, Kebbi, Yobe and Borno State

### 1.3: Problem Statement

Though the performance efficiency of rocket stoves is quite impressive and well documented, however, there is still exists some knowledge gaps that need to be filled, especially, in terms of combustion and thermal efficiencies. Provision of additional excess air supply system in form a motorized fan often results in additional cost and where air intake volume is increased, amounts to loss of useful heat. In addition, it is estimated that for every combustion system with flue gas exhaust system, it is estimated that about 65 % of useful heat is usually lost.

### 1.4: The Three Pot Cascaded Rocket Stove

The thrust of the present work is the development a cascaded three pot rocket stove which exhibits better combustion and thermal efficiencies. As shown in the figures 5, 6 and plate 1 below, this design incorporates some important features which improved the combustion and thermal efficiencies, namely;

i. the combustion chamber is doomed in shaped to allow for swirling,
ii. provision of 2mm air vents on edges of the stove skirt below the combustion chamber,
iii. filling the gaps between the inner and outer cylinders of the combustion chamber with ash, and
iv. re – directing the hot flue gases back to the combustion chamber in a systematic gradient to provide for swirling.

The wood stove consists of three 70cm diameter and 90cm high conically doomed - shaped double walled cylinder combustion chambers made from 2mm mild steel. The inner cylinders are of same height with outer cylinders but fewer diameters. The inner walls are lined with casted refractory materials made from 60% kaolin, 20% clay, 15 % saw dust and 5% silca sand. The gap between the 70 and 65cm diameter cones of the combustion are filled with ash as insulating material. The three stoves are connected together by their exhaust pipes with different cross sectional areas to provide for more air draft necessary for stoichometric ratios and complete combustion. In addition, the stoves are elevated at 10cm height above each other and exhaust of one connects to combustion chamber of the other to mix with the fresh air intake thereby enhancing the combustion efficiency. A sliding iron gaze is incorporated at the base of each stove for ash collection and easy emptying. by and The of 2mmthick 65cmand 70cm diameter The chimney is connected to the last stove and has a pot seating for recovering some in the flue gases.

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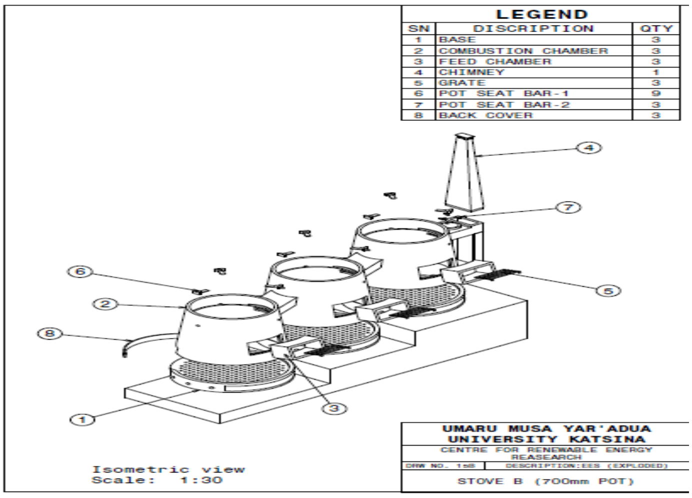


**Figure 5: An exploded view of three pot cascaded stove**

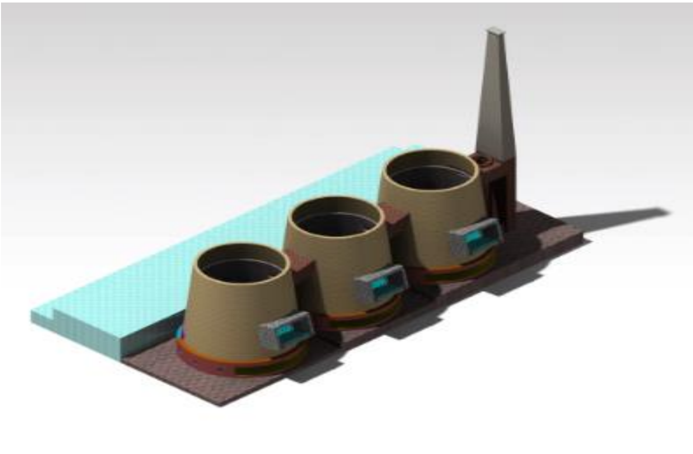

**Figure 5: Front View of the Cascaded Model**

**Plate 1: The Prototype Model of the Cascaded three pots stove**

## 2.0. CASCADED STOVE DESIGN

### 2.1. Design Analysis

### 2.1.1 Design Theory

Improved rocket stove is designed to increase fuel efficiency, reduce harmful emissions associated with combustion of wood as fuel. This is achieved through a combination of increased combustion efficiency and heat transfer. Improving the combustion efficiency is necessary to reduce smoke and harmful emissions that are detrimental to health. Improving heat transfer efficiency can significantly reduce fuel use. Fire is naturally good at its job, but pots are not as good at capturing heat because they are inefficient heat exchangers. In order to reduce emissions and fuel use, it is necessary to first clean up the fire and then force as much energy into the pot as possible. Both of these functions can be accomplished in a well-engineered cooking stove. For better combustion efficiency the following factors need to be considered (Balis *et al.,* 2007).

i. Good drafting into the fire.
ii. Good insulation around the fire to help it burn hotter. A hotter fire burns up more of the combustible gases and produces less smoke.
iii. Avoiding heavy, cold materials like earth and sand to be used around the combustion chamber.
iv. Lifting up the burning sticks off the ground so that air can scrape under the sticks and through the charcoal.
v. Heating only the burning part of the wood because the non-burning wood tends to make smoke.
vi. The cold air limitation while entering the fire by using as small an opening as possible. Small openings into the fire also force the cook to use less wood, which can be burnt more efficiently.
vii. A certain amount of excess air is necessary for complete combustion. Preheating the air helps to maintain clean combustion.

For better fuel efficiency the following way should be concerned (Balis *et al.*, 2007).

i. The increase of the temperature of the gas/flame contacting the pot, having the hot air scrapes against both the bottom and sides of the pot in a narrow channel, using a pot skirt.
ii. The increase of the speed of the hot flue gases that scrape against the pot. The fast gases punch through a boundary layer of still air that keeps slower moving gases from scraping against the surface of the pot (or griddle.) Air is a poor heat transfer medium. It takes a lot of hot air to bring heat to the pot.
iii. Use of metal rather than clay pots because metal conducts heat better than clay .
iv. Use of the wide pots with large diameters. Using a wide pot creates more surface area to increase the transfer of heat

### 2.1.2. Design Calculations

A domestic 50 cm size pot and the corresponding design parameters were selected for a large family size and commercial scale cooking based on table iii. Thus, the design parameters selected for the design of the model are: base internal radius of the combustion chamber, $R_{Bi}$ = 20cm, top internal radius, $R_{Ti}$ = 19cm, height of the combustion chamber,

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$H_C$ = 30cm, height of side air vent, $h_a$ = 2cm; internal diameter of the pot seat, $P_d$ = 50.5cm; overall length of the stove, $L_S$ = 90 cm; height of pot seat chamber, *Hps* = 5cm; measured external temperature of combustion Chamber *To* = 35oC; measured Internal temperature of combustion Chamber, *Ti* = 550oC; thermal conductivity of clay, *K*1 = 1.8W/m (Samuel 2009); thermal conductivity of Aluminum; K2 = 205W/Mk (Samuel 2009).

**Table iii: Inlet and combustion chamber dimensions based on cook pot diameter (Nicholas, 2011)**

| Pot Diameter (cm) | Inlet / Combustion Chamber Diameter (D) (cm | Chamber Area ($cm^2$ ) | K = D/2 (cm | H=K+ D (cm) | Pot Skirt Gap (L) (cm) |
|---|---|---|---|---|---|
| 20 | **12** | **113** | **6** | **18** | **1.6** |
| 21-27 | 14.0 | 154 | 7.00 | 21.00 | 1.5 |
| 28-30 | 16.0 | 201 | 8.00 | 24.00 | 2.0 |
| 31-35 | 16.0 | 201 | 8.00 | 24.00 | 1.5 |
| 36-40 | 18.0 | 254 | 9.00 | 27.00 | 1.9 |
| 41-45 | 18.0 | 254 | 9.00 | 27.00 | 1.6 |
| 46-50 | 20.0 | 314 | 10.00 | 30.00 | 1.9 |

D is the inlet diameter, H is the height of the combustion chamber, K is the distance from the top of the fuel inlet to the outlet of the combustion chamber, and L is the pot skirt gap (modified from Ministry of Energy and Mineral Development, Republic of Uganda and GTZ 2004).

Given that the selected pot size is 50cm diameter, from table iii, above, the combustion chamber area, distance from the top of the fuel inlet to the outlet of the combustion chamber, height of the combustion chamber and the pot skirt gap are 314$cm^2$, 20cm, 30cm and 1.9 cm respectively

## 3.0. MATERIALS AND METHODS

### 3.1. Materials

The list of materials, equipment and instruments used for the experimental tests are:

Wind Anemometer, Thermometers, Thermocouples, Weighing Balances, Stop Watches, 4nos. Models of mud stove, Digital camera, Cooking pot, Rice and Beans, Soup ingredients

### 3.2. Methods

#### 3.2.1. Comparative Performance Testing

The models were subjected to Water Boiling and Controlled Cooking tests**;**

Water Boiling Test (WBT) is to determine Percentage Heat Utilisation (PHU) of a particular stove under same atmospheric conditions measured in %.

Controlled Cooking Test (CCT) is to determine comparatively the quantity of fuel wood consumption in kilogram otherwise known as Specific Fuel Consumption (SFC) and time taken in minutes for cooking a given kilogram of food (specific time spent) with the stove models. This is to ascertain the suitability of the stove in cooking the range of meals in the area of application.

The tests were conducted at Centre for Renewable Energy Research (CeRER) mud stove entrepreneurship production centre.

### 3.3 Experimental Setup

The models were assigned a group, each with a supervisor to ensure proper for monitoring and accuracy of experimental data. A set of required measuring and other equipment for the test were given to each group to avoid hitches during the experimental procedures.

As a precaution, the experiment was conducted under the same atmospheric condition with the mud stove fire magazines facing same direction and to the same angle.

### 3.4 Experimental Procedures

Water Boiling Test (WBT)

The procedures adopted for this include the followings.

i. Some quantity of wood was weighed and recorded by each group.
ii. Cooking pots and lids were weighed and filled up to 2/3 level with a known quantity of water.
iii. The first stove in three cascades was taken to be the single rocket stove.
iv. The pots were placed on the models of mud stoves and the environmental conditions (ambient temperature and wind speed were recorded).
v. Thermometers were inserted from the lids for recording the temperature of the water in the pot and initial temperatures of water were recorded.
vi. The woods were set on fire with two spoons of kerosene and allowed to burn at a low level.
vii. Respective temperatures of water were recorded every two minutes until it boiled.
viii. After boiling, the lids were removed and water in the pots was allowed to boil and evaporate for fifteen minutes.
ix. The weight of remaining water after evaporation was taken.
x. The pots were removed from the wood stoves and fire was put off.
xi. Charcoal from respective stoves were removed, allowed to dry and weighed.
xii. For the other two wood stove in the cascade, the same procedure was followed except that (ii), (iii), (iv), (v), (vi), (vii), and (ix) operations were done for the second pot also simultaneously.
xiii. Outlet chimney temperatures were also recorded. Wood was allowed to burn under the second pot.

### 2.3 Controlled Cooking Test (CCT)

#### 2.3.1 Materials

The same sets of materials, equipment and instruments used for the water boiling tests were used for this test except for rice and beans.

#### 2.3.2 Experimental Procedure

The procedures adopted for this test include:

i. Some quantity of wood was weighed and recorded by each group.

ii. Some quantity of rice and beans to be cooked were **measured** by each group.
iii. Cooking pots and lids were weighed and filled with some quantity of water that could cook the rice and beans.
iv. Respective weights of pot and food items to be cooked were weighed and recorded.
v. The pots were placed on the stoves and the environmental conditions (ambient temperature and wind speeds were recorded).
vi. Thermometers were inserted from the lids for recording the temperature of the water in the pot and initial temperatures of water recorded.
vii. The stop watches were set to start running until when the rice and was done.
viii. Time taken to get food cooked the various stoves were recorded.
ix. The cooked food were removed and weighed.
x. The pots were removed from the wood stoves and fire was put off.
xi. Charcoal from respective stoves were removed, allowed to dry and weighed.
xii. Wood was allowed to burn under the second pot.
xiii. Both WBT and CCT were conducted thrice following the procedures above.
xiv. Mean values of the obtained results are as presented in the following Subsections

**Table iv: Summary of Water Boiling Test Result**

| **Name of Group** | **A** | **B** | **C** |
|---|---|---|---|
| **Wood Mud Stove Make & Model** | **Model A - First Pot Seat** | **Model B - second Pot Seat** | **Model C - third Pot Seat** |
| Ambient Temperature in °C | 23 | 23 | 23 |
| Wind Speed in m/s | 3m/s | 3m/s | 3m/s |
| Moisture content of fuel wood in% | 0 | 0 | 0 |
| Calorific Value of fuel wood in KJ/ kg | 16,200 | 16,200 | 16,200 |
| Initial weight of fuel wood in kg | 5.2 | 5.5 | 4.9 |
| Final weigh of fuel wood in kg | 3.2 | 3.8 | 3.3. |
| Weigh of fuel wood consumed in kg | 2.0 | 1.7 | 1..6 |
| Weight of charcoal remaining | 0.1 | 0.03 | 0.02 |
| Initial weight of pot +lid in kg | 3.1 | 5.2 | 2.0 |
| Initial weight of pot + lid water in kg | 13.1 | 17.2 | 5.8 |
| Initial weight of water in kg | 10 | 12 | 3.8 |
| Final weight of water in kg | 12.9 | 17.01 | 5.2 |
| Weight of Evaporated water in kg after 15 minutes | 0.2 | 0.19 | 0.6 |

**Table v: Summary of CCT Result**

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| Name of Group | A | B | C |
|---|---|---|---|
| **Wood Mud Stove Make & Model** | **Model A - First Pot Seat** | **Model B - second Pot Seat** | **Model C - third Pot Seat** |
| Ambient Temperature in $^0$C | 39 | 39 | 39 |
| Wind Speed in m/s | 3.7 | 3.7 | 3.7 |
| Moisture content of fuel wood in% | 0 | 0 | 0 |
| Calorific Value of fuel wood in KJ/kg | 16,200 | 16,200 | 16,200 |
| Initial weight of fuel wood in kg | 6.0 | 5.1 | 4.6 |
| Final weight of fuel wood in kg | 4.2 | .3..3 | 3.0 |
| Weight of fuel wood consumed in kg | 1.75 | 1.767 | 1..6 |
| Weight of charcoal remaining in kg | 0.3 | 0.1 | .0.1 |
| Initial weight of pot + lid in kg | 2.6 | 5.0 | 2.1 |
| Final weight of cooked food +pot +lid in kg | 6.8 | 12.7 | 9.7 |
| Weight of cooked food in kg | 4.2 | 7.7 | 7.6 |
| Time taken in minutes | 35 | 53 | 45 |

## 5.0. COMPUTATIONAL ANALYSIS AND DISCUSSION OF RESULTS

### 5.1. Computation Analysis of the Results

The procedure and formulae employed for analysis were as follows;
Percentage Heat Utilization (PHU);
Specific Fuel Wood Consumption (SFC)
Specific Time Spent (STS)

5.1.1. Percentage Heat Utilization (PHU)

$$PHU = \frac{\text{Total Heat Energy Supplied}}{\text{Net Heat Supplied}} x100\% \quad 4$$

$$PHU = \frac{M_W C_{PW}(T_W - T_a) + (M_P C_P)T_W - T_a) + ML}{M_{fnet}} \times 100\% \quad ----3$$

Where;
$M_W$ = Initial mass of water;
$C_{PW}$ = Specific heat capacity;
$T_W$ = Final Temperature of water;
$T_a$ = Ambient temperature of water;
$M_P$ = Mass of pot;
$C_P$ = Specific heat capacity of pot;
$M$ = Mass of evaporated water;
$L$ = Latent heat of evaporation of water $\left(\frac{2{,}260kj}{kg}\right)$;
$M_{fnet}$ = Net mass of fuel wood burnt including recovered charcoal;
$C_j$ = Calorific value of fuel wood burnt.

5.1.2. Specific Fuel Consumption (SFC)

$$SFC = \frac{W(1 - M) - 1.5C}{W_f} \quad -------- 4$$

Where:
$W$ = Mass of fuel wood burnt;
$M$ = Moisture content;
$C$ = Mass of remaining charcoal after test;
$W_f$ = Mass of the cooked food.

5.1.3 Specific Time spent (STS)
The time spent in cooking a Kg of cooked food is defined by the expression.

$$\text{Specific Time spent} = \frac{T}{W_f} \quad ------- 5$$

Where:
$T$ = Total time spent in cooking and
$W_f$ = weight of cooked food

The mean values of the analyzed result of WBT and CCT are as shown in table vi.

**Table vi: Summarized Analyzed Results for the Water Boiling & Controlled Cooking Test**

| S/N0. | Models | PHU in % | SFC of wood/kg cooked food | STS In Minutes/kg of cooked food |
|---|---|---|---|---|
| 1 | A | 28 .7 | 0.31 | 8. |
| 2 | B | 42.45 | 0.21 | 7 |
| 3 | C | 43.55 | 0.19 | 6 |

### 5.2. Discussion of Results

Generally, the results showed good performances, in terms PHU, SFC and STS for the single and cascaded modes in comparison with traditional three stone stoves and other ICS. It is observed that the admittance of hot flue gases from stoves A in to B and B in to C respectively, enhanced the Combustion efficiency. Stove units B and C in the model consumed less wood per unit food kg of food cooked which is an indication improved thermal efficiency. Also, less quantity of charcoal was also generated from B and C. lesser time spent in cooking with B and C showed an improved thermal efficiency. It was shown that the first stage stove in the series exhibits lower combustion and thermal efficiency compared to the 2nd and 3rd of the cascaded stoves. The is attributed to the channeling of flue gases to the 2nd and 3rd combustion chambers. resulting in to higher PHU, SFC and STS Values.

## 6. CONCLUSION

A single stage and cascaded rocket stove were developed and tested. The result showed that the single stage and cascaded models have PHU; SFC and STS values of 28.7 %, 42.45% and 43.55%,; 0.31, 0.21 and 0.19; 8,7, and 6 respectively. This suggest that, in Nigeria, development and deployment of this stove can have significant reduction in fuel wood consumption and resultant GHG emissions to the tune of 41,806.75 toe/capita It is shown that the modifications made in providing insulation around the combustion chamber and sizable air inlet to admit adequate quantity of air for combustion, incorporating smoke rings to seal the annulus between the pot and pot-hole, and redesigning the configuration of the pot seat and the position of the gas exit port, have served to increase the thermal efficiency and therefore the percentage heart utilization of the stove. There is a drastic reduction in the smokiness of the stove, making it to be more suitable for indoor cooking in terms of health, comfort and convenience.

## 7. RECOMMENDATIONS

Further modifications on the model should be focused on redesigning of pot seat as well as flue gas exit port. For father improvement on this work, it is recommended consider development of numerical models to validate the results of the experimental prior to developing a prototype.

There is the need to study the effects of the distances and geometry of the cascaded stoves on the combustion and thermal efficiencies of the stove

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