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DESIGN AND FABRICATION OF MULTI-FUEL BIOMASS COOK STOVE THAT WORKS ON BOTH ROCKET AND TOP-LIT UP DRAFT GASIFICATION PRINCIPLES

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ABSTRACT
Heating water and food has been shown to be essential to human health, and heat is produced from different sources like electricity, gas, fossil fuel and biomass, for example. Electricity and gas are cleaner sources of energy used for cooking compared to traditional cooking methods that are used by lots of people in Sub-Saharan African countries, including Sierra Leone. Studies on traditional three stove fire have shown lower thermal efficiency and higher environmental pollution, while using scientific principles to design cookstoves lead to higher thermal efficiency and lower emissions. Consequently, this study was undertaken to address issues of pollution and lower thermal efficiency by designing and producing an improved cook stove wherein scientific principles (Rocket and Top-lit up Draft), technical skills and locally available material were used. The produced stove was tested using procedures of the Water boiling tests. One of the results shows the highest temperature flame of 488$_0$C. Burning rate and specific fuel consumption were 2.47gram/sec and 0.56 Kgwood/Kgwater respectively. Additionally, fire power and thermal efficiency of 8.598kW and 41.37% respectively were also obtained. These results show that using scientific methods and skills to produce improved cookstoves will result in higher thermal efficiency and lower fuel consumption. These results do not only reflect positively on the environment, but on the health of women and children, considering their involvement in collection of wood used as fuel for cooking.

Keywords: Improved Cookstove, Heat transfer, Thermal efficiency, Environmental pollution

INTRODUCTION

In developing countries, 2.3 billion people use solid biomass such as wood and agricultural wastes as fuel on traditional open fire (three stone fire) stoves to produce heat needed for cooking and heating (IEA, 2022b). Inefficient burning of biomass, though it is a renewable energy resource, can emit pollutants that are harmful to human health and the environment (WHO, 2022). In Sierra Leone, 92% of the population uses cooking fuels that are inefficient and highly polluting (Stoner et al., 2021). Sierra Leone is one of Sub-Saharan African, countries with limited access to clean cooking methods, especially in rural communities even though it has abundant energy resources that are widely available (Chiu, 2023). A transition from biomass to stoves using Liquid Petroleum Gas, LPG, and electricity for household energy use can reflect positively on the environment and human health (Floess et al., 2023), given that these stoves emit less pollutants. However, access to electricity and low financial status of most rural dwellers pose a challenge for their use.

Studies on cookstoves that are carefully designed and fabricated have shown to burn less solid biomass wood fuel (Sweeney, 2017). Therefore, such stoves can help in addressing issues of environmental pollution, given that fewer trees are cut down. Accordingly, improved cookstoves have shown to produce less pollutants and can reduce fuel usage by 20-75% if performance standards are enforced by regulators and observed by users (IEA, 2022a). Therefore, biomass improved clean cooking stoves are better alternatives to traditional methods of cooking. For cook stoves to work effectively, design factors such as airflow rates, dimension of the combustion chamber and insulation have significant effects on the performance of the stove (Tesfaye et al., 2023; Pasha et al., 2023). In this regard, a stove that is capable of using different solid biomass fuels and can be operated on dual combustion principles (Rocket and Top-lit up Draft) can help in addressing issues of health and deforestation. Therefore, this study is undertaken to come up with the design and production of a biomass cookstove that can help address these challenges.

Literature Review

Requirements for complete combustion

Knowledge of temperature difference, thermodynamics, is essential in the evaluation of heat flow, as it is the basic element in the design of thermal equipment like nuclear reactor cores, boilers, heat exchangers, stoves, etc. Therefore, thermodynamics is essential in explaining the heat transfer in cookstoves. When a spark, fire, is applied to wood, white smoke is produced, followed by a glowing flame that eventually leads to smaller quantities of charcoal and grey ashes (Reed and Golden, 1988). Chemical energy is released when biofuel goes through the combustion process. This process involves oxidation with the combustible components like flue gases which produces heat energy (Van Loo and Koppejan, 2008). Cookstoves can be supplied with primary air through two main methods: Natural and forced drafts (Ochieng, 2013). Natural draft can affect air flow rates and combustion conditions, in the sense that the flow conditions in the stove can be controlled through design parameters, combubut too low and too high flow rates occur in practice (Anderson, 2007). Low draught can lead to inadequate air thereby causing fire to be extinguished. Smoldering combustion conditions are due to a lack of oxygen. On the contrary, too high a draught leads to excess air which increases combustion temperature and gasification rate. Forced draughts are used in continuous combustion operations wherein air blowers or fans are used to provide constant or regulated supply of primary air as and when required. This draught method can significantly increase gasification and combustion temperatures (Tissari, 2008). Given that cookstoves require heat, then combustion stage is essential to focus on as regards design and technical geometry

Proximate and Ultimate Properties and Molar Ratios

Wood is an organic material that is primarily made up of carbon (C), oxygen (O) and hydrogen (H). It is composed mainly of cellulose, hemicellulose, lignin and extracts in the given percentages: 47.62%, 39%, 11.23% and 2.15% respectively (Ragland *et al.*, 1991). Proximate and Ultimate analyses including Molar ratios for wood biomass are shown in table 2.1. Low moisture content results are essential for swift heat transfer in cookstoves (WHO, 2022). High moisture content, contrarily, needs additional heat to remove moisture before heat is transferred. High volatile content in wood is more reactive leading to production of higher heat with production of less fixed carbon, as compared to low volatile content (Reed, 1981).

Table 2.1 Proximate and Ultimate Analysis and Molar Ratios of Wood

Proximate analysis (Mass percent)	
Moisture	3.07
Ash	3.38
Volatiles	80.87
Fixed Carbon	12.68
Ultimate analysis (Mass percent)	
Hydrogen	6.62
Carbon	46.09
Oxygen	47.19
Nitrogen	0.10
Sulphur	–
Molar Ratios	
H/C molar ratio	1.72
O/C molar ratio	0.76
C/N molar ratio	537
Empirical Formula	$CH_{1.72}O_{0.76}N_{0.002}$

Source: Mondal and Varma 2016)

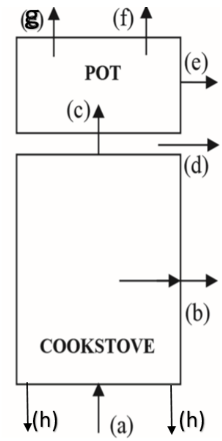
Ultimate fuel analysis is important, for it is used to determine air needed for emissions levels and combustion. From table 2.1, there is a minimal presence of Nitrogen, 0.1%, with no sulphur presence. These results imply that wood can be used for the production of heat energy needed in cookstoves, given that, there is no presence of Sulphur and its oxides (SOX), and very low presence of Nitrogen and its oxides (NOX) (Ragland *et al.*, 1991). It is important to note that SOX and NOX are mainly responsible for emitting pollutants (Mondal and Varma, 2016). Lower ratio of H/C and O/C shows that the wood has greater energy content as explained by the Van Krevelen diagram (McKendry, 2002). Accordingly, it is suitable for thermo-chemical conversion processes required in cookstoves.

Heat transfer processes in a Cookstove

Combustion of solid biomass converts chemical energy into thermal energy which is essential heat needed in biomass cookstoves (Geller and Dutt, 1982). An important element in heat transfer in cookstove is Fire power, which is the amount of thermal energy produced per unit time, and it is expressed in Kilowatt (kW). The fire power provides the total energy, a, of the stove, as seen in figure 2.1. The surrounding receives some of the energy from the body of the stove, b, through radiation and convection. Pot and its contents receive some of the energy, c, through convection.

The atmosphere also receives some of the energy including flue gases, d, due to convection and radiation. On the contrary, the walls of the pot lose heat, e, through convection to the atmosphere. At the upper portion of the pot, heat is lost through convection, f, and evaporation, g, while conduction heat loss is from the body of stove to the ground is represented as h (Sutar *et al.*, 2015). According to figure 2.1, heat transfer through convection is essential in cook stove, therefore, it is considered in the design of the stove for this study. Accordingly, reduction of these losses is one of the objectives of this study.

(a) Fire Power
(b) Heat loss to and through stove body
(c) Energy absorbed by pot and water
(d) Flue gas and direct radiation losses
(e) Heat loss from vessel walls
(f) Exaporation losses
(g) Convective losses from water/lid surface
(h) Conduction heat loss from stove to ground



Figre 2.1: Heat Transfer Contributions
Source: Sutar *et al.* (2015)

Traditional Cooking

The three-stone fire (TSF) is a traditional cooking method that is widely used in rural communities of developing countries, especially Africa. It is made up of three stones that are placed on the ground in the shape of a triangle within which fuel, mostly wood, is placed. A pot or pan is placed on top of the stones, as portrayed in figure 2.2.

Figure 2.2: Three-stone fire in Sierra Leone
Source: Chiu (2023)

It requires little or no technicalskill to make and operate; less time to set-up with little tending time. On the contrary, primary air is reduced due to the surface area of the wood exposed and heat lost through conduction. Increased radiation losses resulting from the charcoal and fire to the surroundings. Incomplete combustion occurs when the amount of primary air available to react with the fuel is reduced, resulting in an increase in Indoor Air Pollution (IAP) (Bryden, 2010). Therefore, the thermal efficiency of TSF is low, 15%. This is due to its consumption of huge amounts of fuel (Ochieng, 2013). It is worth noting that, better fuel efficiency leads to lower emissions, which are factors needed to reduce health risks associated with cookstoves. An investigation into how both emissions and fuel consumption can be reduced with the increasing thermal efficiency, is the aim of this study.

Traditional to Improved Solid Biomass Cookstoves

There are various types of improved cookstoves, however, the widely used ones are Rocket elbow or L stove and Top Lift Up Draft (TLUD), as shown in figures 2.3a and 2.3b respectively. The rocket elbow stove takes its name from the shape of its combustion chamber Fuel is placed tangential to the axis of the combustion chamber, as shown in figure 2.3a. It works on continuous feeding of fuel which does not require removing the pot from the stove for fuel to be added, however, it requires more tending time (Winiarski, 1982). In the TLUD stove, fuel is placed in the combustion chamber and ignition is done at the top. It is considered a mini gasifier and primary air can be supplied through natural or forced draft (Sweeney, 2017). Combustion is due to a mixture of draft from the bottom of the chamber and fire produced by the fuel, however, when it runs out of fuel, the pot has to be removed for new fuel to be added (Birzer *et al.*, 2013). Gasification, pyrolysis and combustion methods of heat energy transfer principles are similar for both Rocket stove and Top-lit up Draft (TLUD) operations. Unlike traditional cookstoves, improved cookstoves are more portable and can be used both indoors and outdoors (Pasha *et al.*, 2023). Experimental results suggest that new wood -burning cookstoves should be carefully designed, constructed and operated with the aim of achieving improved thermal efficiency (Anderson, 2007; Bryden, 2010; Tryner *et al.*, 2014; Sutar, 2022). Improvement on the structure of the combustion chamber, distance between the end of the stove and the bottom of the pot are essential factors for better heat transfer (Sweeney, 2017; Pasha *et al*., 2023).

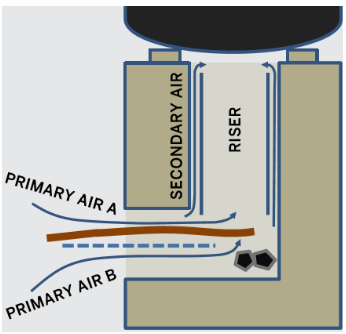


Figure 2.3a: Rocket elbow or L stove.
Source: Winiarski (1982)

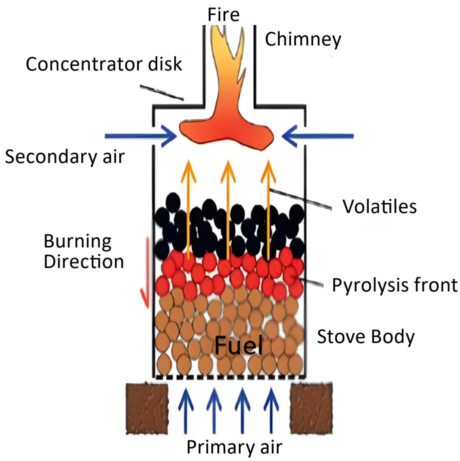


Figure 2.3b: Top-Lift Up Draft (TLUD) Stove.
Source: Anderson (2007)

When compared with TSF, Rocket elbow stoves tests results show a reduction in fuel saving of 41% with a reduction in CO and PM25 by 46% and 56% respectively (Bryden, 2010). Jetter et al. (2012) conducted an experimental study on TLUD forced draft cookstove and achieved an efficiency of 38% with little emissions of CO and PM2.5. However, Birzer et al. (2013) contend that emission is increased when dung is used as the fuel. When compared with traditional biomass cookstoves, improved biomass cookstoves are found to be more efficient;consume less fuel with emit less pollutants (Medina et al., 2017). Latest studies on stoves have shown that improved cookstoves are more efficient than traditional TSF stoves, as they consume less fuel and emit less pollutants (Demie et al., 2019; Mekonnen, 2020; Jyoti et al., 2021; Sutar, 2022; Tesfaye et al., 2023; Pasha et al., 2023).

Armstrong et al. (2021) conducted a study in Sierra where ethanol was used as fuel in cookstoves as an alternative solid biomass fuel. Results show users experienced improved comfort and time savings as compared to stoves using wood and charcoal. However, there were concerns regarding alcoholism, culture and access to technology A study conducted in Sierra Leone by Lahai et al. (2023) reveals that the thermal efficiencies of the two most popular charcoal burning stoves, Wonder and Metal, are 19.67% and 17.79%. The study alsoreveals that these stoves have low burning rates compared to other improvedcookstoves. Natural gas, Liquefied Petroleum Gas (LPG) and ethanol are widely used as fuels in stoves for cooking and heating, and they produce low levels of Carbon monoxide (CO) and Particulate Matter (PM2.5) during combustion (WHO, 2021). Solar and electric energy are considered the cleanest and they produce no direct CO and PM25. Solid biomass is another form of fuel that is widely available but produces high levels of pollutants. It is important to note that the aforementioned fuels, except biomass, are expensive and out of the reach of the urban and rural poor people, especially those living in Africa, including Sierra Leoneans. Solid biomass, wood, for instance, is used as fuel in traditional stoves such as three-stone fire, which has low thermal efficiency. However, previous and recent studies have shown that, cookstoves can burn solid biomass fuel more efficiently with low levels of CO and PM2.5, when scientific principles and applications are used (Bryden, 2010; Jetter et al. (2012; Demie et al., 2019; Mekonnen, 2020; Jyoti et al., 2021; Sutar, 2022; Tesfaye et al., 2023). This study sets out to use biomass as fuel in cookstoves that are designed to work on both TLUD and rocket principles, which the reviewed literatures did not reveal. Accordingly, scientific principles and technical methods are used as tools to reduce fuel use and the quantity of the pollutants produced.

WHO and ISO Criteria for Clean Cookstove

The World Health Organization (WHO) including other international organizations like, International Organisation for Standardisation (ISO),have developed guidance, which countries can implement in order to set standards as regards the performance of cookstoves with the aim of protecting the health of users (WHO, 2024). An agreement was established, which is referred to as International Standard Organisation Workshop Agreement (IWA 11:2012). Accordingly, five performance indicators were developed and they are: durability of biomass cookstoves, safety, thermal efficiency, fine particulate matter emissions and carbon monoxide emissions. Laboratory test results are rated along six levels for each of the indicators, 0 to 5 (0: for lowest performing cookstove to 5: for highest performing cookstove). Table 2.2 reports default values of these voluntary performance targets. Traditional, improved and advanced cookstoves are categorized according to the six levels. Most traditional cookstoves fall within category 0 to 1. Improved biomass cookstoves fall within rating 2–3 whereas advanced biomass cookstoves are within levels 3–5. An increase in tier rating reveals increased efficiency and safety score but decreased CO and PM emissions and durability score. However, a decrease in durability score means the stove becomes durable.

These classifications, together with labels on stoves, can help consumers make better decisions on stove purchases to achieve better health benefits. Major In-door Air Pollutants (IAP) are: particulate matter of size less than 10 µm (PM_{10}) and less than 2.5 µm ($PM_{2.5}$), carbon monoxide (CO) and nitrogen dioxide (NO_2) (WHO, 2021). WHO guidelines set permissible limit of exposure to CO emissions for 1 hour as 35 mg/m3, for 8 hours it is set at 10 mg/m3, and for 24 hours this limit is set at 7 mg/m3. It is of utmost importance for researchers to be knowledgeable about the safer limits of these pollutants, as they add to global warming.

Table 2.2 Default values of voluntary performance targets for biomass cookstoves (IWA 11:2012)

Tier	Thermal efficiency (%)	CO (g/MJ_d)	PM (mg/ MJ_d)	Safety score	Durability score
5	≥ 50	≤ 3.0	≤ 5.0	≥ 95	< 10
4	≥ 40	≤ 4.4	≤ 62	≥ 86	< 15
3	≥ 30	≤ 7.2	≤ 218	≥ 77	< 20
2	≥ 20	≤ 11.5	≤ 481	≥ 68	< 25
1	≥ 10	≤ 18.3	≤ 1031	≥ 60	< 35
0	< 10	> 18.3	> 1031	< 60	> 35

MJ_d: Mega Joule of energy delivered

Adoption of Biomass Cookstoves

Acceptance by users of the stoves is also important in the design of a cookstove, and should be considered by researchers (Saraswati, 2018). Acceptability is increased if stove is easy to manufacture, operate, cheap, emits less smoke, durable, safe and easy to repair (Bryden, 2010). Anderson *et al.* (2007) point out that adoption of improved cookstoves is contingent on Cultural, Social and functional factors. Further barriers include; low family income, lack of involvement of women in decision making processes of the home, lack or little education of women, inadequate knowledge of the influence of inefficient biomass cookstove on the environment and health (Saraswati., 2018). Perception and knowledge of users are also relevant in the acceptance of cookstoves (Changuda *et al.*, 2017). Effective communication is an important factor for better uptake of improved cookstoves. The outcomes of both clean cooking stoves and traditional forms of cooking should be understood by policymakers and stove users for effective uptake of improved cookstoves. Furthermore, places of learning, worship, work and entertainment should be involved in the education process regarding these stoves (IEA, 2023). Therefore, it is pertinent for researchers to consider these factors in order to design and produce cookstoves that are less polluting but with improved heat transfer leading to better thermal efficiency.

The review has shown that the use of improved cookstoves can lead to less fuel usage and a reduction in environmental pollution, given that less trees are cut down. Notwithstanding the positive attributes, there is need for further improvement in the form of: cooking time, combination of fuel feed methods, thermal efficiency reduction in environmental pollution. It is also worthy of note that, reviewed literatures did not reveal studies that have combined both rocket and Top-lit up Draft principles in cookstove design and production, especially in Sierra Leone. As a consequence, this study is undertaken to come up with a design to address these challenges.

DESIGN OF STOVE – MATERIALS, METHODS AND FORMULAE

Materials

Design and Construction Procedures

Mild steel is used to fabricate all parts of the stove, as it is locally available and cheaper than stainless steel. Additionally, it has a low thermal expansive rate with high melting point (above 1000^{0}C), which are properties required for the design of this stove (Incropera and DeWitt, 2002). In order to ensure easier reproduction of the stove, locally available tools and equipment together with simple steps, were used. Basic fabrication tools such as hacksaw, chisel, metal ships, hammer, centre punch, plier and steel rule. Arc welding machine was used to join the parts, while a hand electric grinder was used for smoothing rough edges. Design of the stave is based on a combination of rocket stove and Top-lit up Draft (TLUD) operations, in which gasification, pyrolysis and combustion heat energy transfer principles were employed. The combustion chamber is made from 3mm thick mild steel plate with an internal diameter of 180mm and height 268mm. It is designed to burn different solid biomass fuels like, like charcoal, wood and its shavings, dry fruit shells and nuts. A metal grate designed with horizontal rods, 6mm in diameter, was fitted at the base of the reactor with the intention of improving primary air flow. The grate also makes it easier for ash and little charcoal to drop from the combustion chamber to the ash compartment. Primary air is supplied by natural drafts. An outer mild steel shell fitted concentrically outside of the reactor whose thickness, diameter and height are 1mm, 360mm and 380mm respectively. The space between the combustion chamber and outer shell provides insulation intended to reduce heat loss due to radiation and convection (Incropera and DeWitt, 2007). Figure 3.1 shows 3-Dimensional view of the stove, while figure 3.2 and table 3.1 show exploded view of all parts of the table and names of the stove respectively. Figure 3.3a shows welding progress, while 3.3b shows completed internal structure of the stove. Figures 3.3c and 3.3d show dried mango seeds and charcoal being used as fuels respectively. Flame height is shown in figure 3.3e. The completed stove and its combustion principles are shown in figures 3.4 and 3.5 respectively.

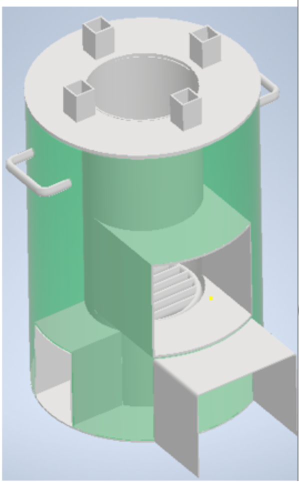


Figure 3.1:3-Dimensional view

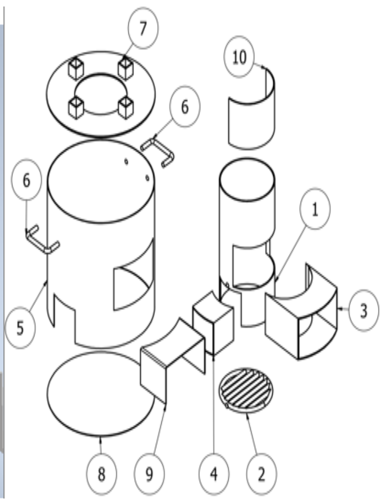


Figure 3.2: Exploded view of parts

Parts List

Item	Quantity	Part Number
1	1	Combustion Chamber
2	1	Grate
3	1	Fuel Duct
4	1	Ash Duct
5	1	Outer Body
6	2	Handle
7	1	Pot Rests
8	1	Bottom Plate
9	1	Wood Rest
10	1	TLUD Converter

Figure 3.3a: Welding work

Figure 3.3b: Internal structure

Figure 3.3c: Dried Mango seeds as fuel

Figure 3.3d: Charcoal fuel

Figure 3.3f: Pot atop stove

Figure 3.3e: Height of flame

Figure 3.4: Combustion on rocket Principle

Figure 3.5: Combustion on TLUD Principle

3.1: Methods and Formulae

3.1.1: Thermal Conduction Resistance

Thermal resistance is a measure of how difficult it is for heat to be conducted in a material, its formula is essential in cookstove design, as it helps to adopt methods that will reduce heat loss during operation (Cengel, 2007). The combustion chamber of this stove is a hollow mild steel cylinder that is enclosed by an outer shell with air as insulation.

3.1.2: Heat flow through the walls of a cylindrical vessel

Figure 3.2a shows the combustion chamber designed for this study, and it is made of mild steel. It is a hollow cylinder of length, L, with internal and external radii of r_1 and r_2 respectively.

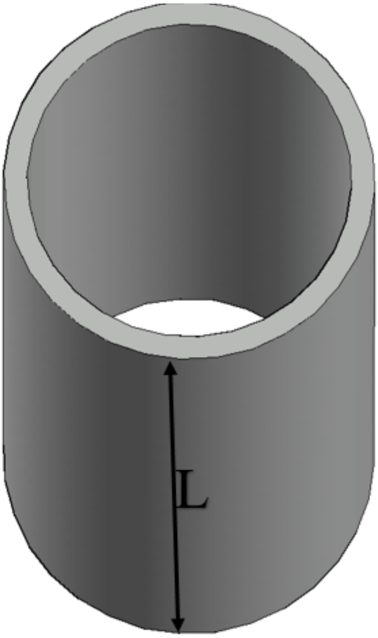


Figure 3.2a: Hollow cylinder

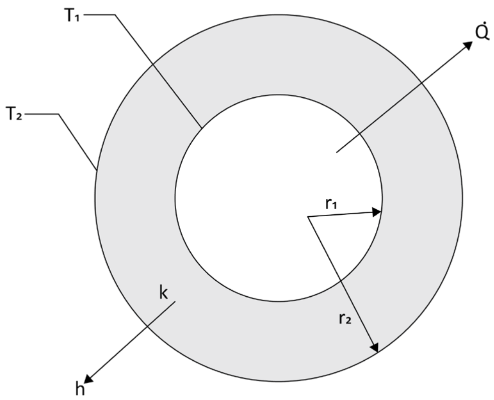


Figure 3.2b: Cross section/layer of a cylinder
Source: Cengel and Michael (2011)

Consider figures 3.2a and 3.2b and adopting assumptions made by Fourier (1878): time remains constant across the thermal resistance network; heat transfer is steady and one-directional; thermal conductivities are constant and; thermal contact resistance at the interface is negligible. The two surfaces of the cylindrical layer are maintained at constant temperatures and. Therefore Q = Constant. Then, Fourier's law of heat conduction for heat transfer through the cylindrical layer is expressed as:

$$\dot{Q} = -KA\frac{dT}{dr} = KA\left(-\frac{dT}{dx}\right) \text{ = Eqn 1}$$

The minus sign appearing in Eqn 1 is due to the convention that the heat is taken to be positive in the direction of increasing r and also ensures that heat flows in the direction of decreasing temperature, thus satisfying the second law of thermodynamics. The term (dT/dr) is defined as the temperature gradient and carries a negative sign. Where Q is the heat flow rate (W), r is the direction of heat flow (m), k is the thermal conductivity (W/mK), T is the temperature (^{0}C), A = (2πL), m^2, is the heat transfer area perpendicular to the flow of heat and depends on the radius, r.

Dividing both sides by (2πL) and performing variable separations and integrating from r = $r_1$to r = $r_2$in which $T(r_1) = T_1$ and $T(r_2)$ = T2 , produce:

$$\int_{r-r_1}^{r_2} \frac{Q}{A} dr = -\int_{T-T_1}^{T_2} KdT \text{ = Eqn 2}$$

Substituting for A = 2πL

$$\dot{Q} = 2\pi rL\frac{T_1 - T_2}{\ln\left({}^{r_2}/_{r_1}\right)} \text{ = Eqn 3}$$

Also, Q = constant, equation 3.3 can be rearranged to give equation 4.

$$\dot{Q} = \frac{T_1 - T_2}{R} \text{ = Eqn 4}$$

R is the conduction resistance of the layer of the cylinder, therefore, thermal resistance, TR can be expressed as:

$$TR, = \frac{T_1 - T_2}{\text{Heat flow,Q}} = \frac{\text{Temperature difference }(\Delta T)}{\text{Heat flow }(Q)} \ [°C/W]. \text{= Eqn 5}$$

3.1.3. Heat Transfer Coefficient

Consider a cylinder with a layer and exposed to heat transfer through convection on the inside and outside with temperatures and and convection heat transfer coefficients of h_1 and h_2 respectively, as sketched in figure 3.3.

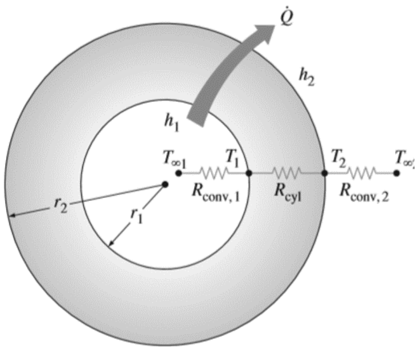


Figure 3.3: Heat transfer through Conduction and Convection

Source: Cengel (2007)

Accordingly, under steady state conditions of heat transfer, the network for thermal resistance for this scenario is made up of two convections and one conduction resistances connected in series, expressed mathematically as (Cengel, 2007):

$$\dot{Q} = \frac{T_1 - T_2}{R_{total}} \quad = \text{Eqn 6}$$

Where,

$$R_{total} = R_{conv.1} + R_{cyl} + R_{conv.2} \quad = \text{Eqn 7}$$

$$R_{total} = \frac{1}{(2\pi L r_1)h_1} + \frac{\ln(r_2/r_1)}{2\pi L k} + \frac{1}{(2\pi L r_2)h_2} \quad = \text{Eqn 8}$$

Also note that the thermal resistances are in series, and thus the total thermal resistance is determined by simply adding the individual resistances, just like the electrical resistances connected in series. Applying Newton's law of cooling relating to convection:

$$\dot{Q} = hA(T_1 - T_2) \quad = \text{Eqn 9}$$

h = convection heat transfer coefficient of the fluid

Where A is the convection surface area (m^2), is the surface temperature of the wall (K) and represents the bulk fluid temperature (K).

$$R = \frac{1}{hA} \quad = \text{Eqn 10}$$

A knowledge of conduction resistance and convection heat transfer coefficients are essential in designing a cook stove, in order to address heat is lost through these processes.

3.1.4. Thermal Performance Components

Thermal efficiency - Thermal efficiency of a biomass cook stove is defined as the ratio of the actual energy utilised by the pot and its contents, per unit of time, to the fire power obtained through combustion of the fuel. It is a measure of the percentage of heat produced by the fuel needed to perform a task, for instance, to boil water in a pot. It is calculated using this equation (Geller and Dutt 1982):

$$\eta = \frac{\text{Total Heat energy required to boil water + evaporation energy}}{\text{Heat energy released by a given quantity of fuel}} \text{ x } 100\% = \text{Eqn 11}$$

$$= \frac{C_W * W_W(T_f - T_i) + L_{EW}(W_i - W_f)}{M_f C_f} * 100\% = \text{Eqn 12}$$

Where,

M_w = Mass of water in pot

C_w = Specific heat capacity of water

M_{WV} = Mass of water vapourised

M_F = Mass of fuel consumed

C_f =Calorific value of fuel (wood)

L_{EW} = Latent heat of evaporation of water

Aside thermal efficiency, there are other metrics required to achieve more reliable results thereby improving performance of the stove, such as: fire power, specific fuel consumption, water boiling rate, fuel burning rate, fuel use reduction.

Fire power is a vital metric of heat output of the stove and, it is calculated as (Berrueta *et al.*, 2008):

$$\text{Fire power (FP)} = \frac{\text{Fuel consumed (g) x calorific value (J/g)}}{\text{Time to boil water (min) x 60}} = \text{Eqn 13}$$

Burning Rate - is the amount of fuel used in the experiment with respect to time spent. It helps to show whether the stove is effective in utilising fuel. The formular is given as:

$$F = \frac{1}{t}\left[\left(\frac{100 \text{ X } M_{iw}}{100 + X}\right) - \left(\frac{M_C H_C}{H_{Wd}}\right)\right] = \text{Eqn 14}$$

Where,

M_{iw} = Initial mass of water

M_c = mass of charcoal

H_c = Calorific value of charcoal

H_{wd} = Heat capacity of wood

X = moisture content and

t = time

Specific Fuel Consumption (SFC) - is the mass of fuel required (grams) to produce a unit of output is referred to as specific fuel consumption. Residual mass of water in the pot at the end of the test is referred to as unit of output (kg). SFC is expressed as g/kg and it is calculated using this formula (Patil and Singh, 2004**):**

$$SFC = \frac{\text{Fuel consumed (g)}}{\text{Effective mass of water boiled (g)}} \text{ x 1000L (g/litre)} = \text{Eqn 15}$$

$$SFC = \left[\frac{M_f(1 - X) - 1.5M_C}{M_{iWT}}\right] = \text{Eqn 16}$$

Where, M_f is mass of fuel, M_C is mass of charcoal and initial mass of water is M_{iwt}.

Power Consumed for Boiling - This gives the energy used to boil the water used in the experiment. It expresses the rate at which the stove does its work, given below:

$$PC = \left[\frac{M_F(1-X)-1.5M_C}{60t}\right]C_f \quad = \text{Eqn 17}$$

3.1.5. Water Boiling Test

Water Boiling Test is carried out to find out whether a cookstove is both effective andefficient in burning fuel to achieve results (Dutt and Geller, 1980). The experiment was carried out in a village in Gloucester, in the city of Freetown, Sierra Leone. An aluminium pot and its lid were carefully cleaned and weighed, and 4kg of water poured in the pot. A bundle of split wood consisting of different sizes was weighed and moisture content recorded was placed inside the combustion chamber and then ignited.

The wood was allowed to burn until a constant temperature was achieved. Initial temperature of water in the pot and ambient temperature were recorded, thereafter the pot, water and lid were placed on top of the stove and that time was recorded. A kitchen environment was observed during the experiment. Temperature of water was recorded every 2 minutes until vigorous boiling takes took place. The final temperature was recorded. Pot and boiled water were taken from the stove and weighed. Flame on the remaining unburnt wood was quickly extinguished using sand, thereafter, sand was removed from wood. Weights of Ash, charcoal and remaining wood were recorded. Steps followed in this experiment are in accordance with water boiling steps outlined by Global Alliance for Clean Cookstoves (2014).

ANALYSES AND DISCUSSIONS OF RESULTS

Parameters obtained during water boiling test are shown in table 4.1, while parameters of known values are shown in table 4.2. These two sets of parameters were used to carry out the required thermal calculations. The water boiling test utilizes solid wood biomass to boil 4kg of water at 100^0C, wherein initial temperature is 25^0C.

Table 4.1: Parameters obtained during water boiling test.

No	Parameter (Description)	Value
1	Initial mass of water,	4kg
2	Final mass of water,	3.8kg
3	Weight of water evaporated during boiling, M_{WEV}	0.2kg
4	Initial Temperature of water,	25^0C
5	Final temperature of water,	100^0C
6	Mass of empty pot,	3 kg
7	Initial mass of fuel (wood),	3kg
8	Final mass of fuel (wood) at the end,	1.55kg
9	Mass of fuel wood consumed in boiling,	1.0kg
10	Mass of charcoal,	0.4kg
11	Moisture content of fuel wood, X	6%
12	Time taken to boil, T	8 minutes

Table 4.2: Parameters of Known Values

No	Parameter (Description)	Value
1	Latent heat of evaporation of water,	2260 kJ/kg
2	Thermal conductivity of mild steel, K	45W/mK
3	Thermal conductivity of wood ash, $K_{wood\ ash}$	0.2W/mK
4	Conductive heat transfer coefficient, h_{in}	60W/m^2
5	Conductive heat transfer coefficient, h_{out}	20W/m^2
6	Specific heat capacity of pot (Aluminium),	0.9 kJ/kg^{0}C
7	Specific heat capacity of water,	4.186 kJ/kg^{0}C
8	Calorific value of charcoal, H_C	29,000kcal/kg
9	Calorific value of fuel (wood), C_F	4127.25 kcal/kg

4.1: Heat required to boil water

Using the formula (Global Alliance for Clean Cookstoves, 2014):

$H = mc\theta$ = Eqn 18

Where H is the heat required, m is the mass of water, C is the specific heat capacity of water and θ is the temperature difference. Therefore heat, H, required to perform task is: (4.186) x 4 x (100 - 25) = 1255.8kJ. Therefore, fuel conversion efficiency of 100% will require 1255.8kJ of energy to boil 4kg of water. Calorific value of wood is 4127.25kJ/kg, then mass of wood needed is 1255.8/4127.25 = 0.3043kg. Assuming a thermal efficiency of 34%, and energy loss of 66%. For a thermal efficiency of 34%, mass of fuel wood needed will be: 0.3043/34% = .3043/.34 = 0.895kg. Therefore, the combustion chamber for this study has a volume that is large enough to accommodate 0.895kg of fuel wood. As discussed earlier in the literature review, 100% efficiency of cookstove is practically not achievable, because about two thirds of heat generated is lost to radiation and convection (Zube, 2010), hence 34% as thermal efficiency is an assumption that is realistic.

4.2: Steady Rate of Heat Loss

A cross-section of the combustion chamber of the stove and outer shell is shown in figure 4.1.

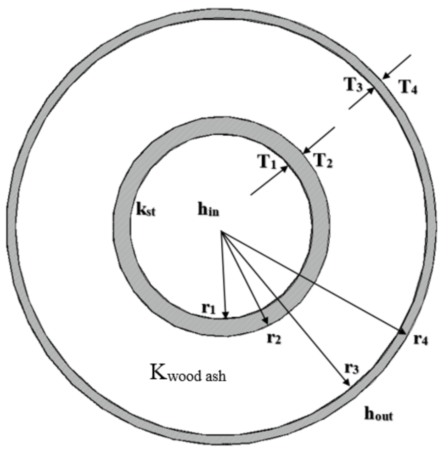


Figure 4.1: cross-section of the combustion chamber and insulation

Applying the principles and formulae presented in section 3, and considering assumptions made, thermal resistances of the stove can be calculated using the procedures and parameters of the stove obtained through the design: A_1 = , A_3 = , = 90mm, = 93mm, = 180mm, = 181mm, 268mm, = 380mm, h_{in} = 60W/m^2, h_{out} = 20W/m^2, K_{st} = 45W/mK, $K_{wood\ ash}$ = 0.2W/mK

$$A_1 = 2\pi \text{ x } .268 \text{ x } .09 = 0.152\text{m}^2$$

$$A_3 = 2\pi \text{ x } .380 \text{ x } .180 = 0.430\text{m}^2$$

The thermal resistance network for this stove involves four resistances in series, as sketched out in figure 4.1. Calculations for individual thermal resistances give:

$$R_1 = R_{convec.1} = \frac{1}{h_{in}A_1} = \frac{1}{h_1 A_1} \quad = \text{Eqn 19}$$

$$R_1 = \frac{1}{60 \text{ x } \mathbf{0.152}} = 0.110\text{K/W}$$

$$R_2 = \text{Combustion chamber} = \frac{\ln(^{r_2}/_{r_1})}{2\pi L_1 K_1} \quad = \text{Eqn 20}$$

$$R_2 = \frac{\ln(^{93}/_{90})}{2\pi \text{ x } .268 \text{ x } 45} = \frac{0.0328}{75.775} = 0.0004238\text{K/W}$$

$$R_3 = R_{\text{wood ash}} = \frac{\ln(^{r_3}/_{r_2})}{2\pi L_3 K_2}. \quad = \text{Eqn 21}$$

$$R_3 = \frac{\ln(181/93)}{2\pi \text{ x } 0.380 \text{ x } 0.2} = \frac{0.666}{0.477} = 1.395\text{K/W}$$

$$R_4 = R_{convec.2} = \frac{1}{h_{out}A_3} \quad = \text{Eqn 22}$$

$$R_4 = \frac{1}{20 \text{ x } 0.43} = 0.116 \text{ K/W}$$

Given that all the resistances are in series, the total heat resistance of the stove is:

$$R_{total} = R_1 + R_2 + R_3 + R_4 \quad = \text{Eqn 23}$$

$$R_{total} = 0.110 + 0.0004238 + 1.395 + 0.116 = 1.621\text{K/W}$$

Then the steady rate of heat loss from the heat produced by fuel biomass becomes: Q = W (per m pipe length). Using equations 9 and 10 gives:

$$\dot{Q} = hA(T_1 - T_2) \quad = \text{Eqn 9}$$

$$\dot{Q} = \frac{T_1 - T_2}{R_{total}} \quad = \text{Eqn 10}$$

$$= \frac{488 - 28}{1.621} = 283.775\text{W}$$

From the calculations, the thermal resistance of the combustion chamber is small relative to R3 and R4 (insulation), and can be neglected without causing any significant effect on heat transfer. Additionally, the combustion chamber can be considered to be isothermal, as the temperature drop across its thickness is close to zero.

4.3.1. Thermal Performance of the stove

The thermal efficiency formula in section 3, Equation 11, and it is stated thus:

$$\eta = \frac{\text{Specific heat capacity of water} \times W_w(T_f - T_i) + L_{EW}(W_i - W_f)}{M_f C_f} * 100\%$$

Using data from tables 4.1 and 4.2, and substituting them in equation 11 gives:

$$\eta = \frac{4.186 \times 4(100-25) + 2260(3-2.8)}{1 \text{ x } 4127.25} * 100\% = 41.37\%$$

The thermal efficiency of this stove falls on tier 4 of the International Standard Organisation Workshop Agreement, IWA. The interpretation of this tier is that this stove emits less CO and $PM_{2.5}$ than traditional cookstoves. Additionally, its safety are durability scores are > 86 and < 15 respectively, which are far better than safety scores of traditional cooking stoves with safety and durability scores of > 60 and < 35 respectively. An efficient cookstoves attracts users of traditional forms of cooking to improved cookstoves that use less fuel and are less polluting.

4.3.2. Fire Power

From section 3, fire power equation is equation 13, stated as:

$$\text{Fire Power (FP)} = \frac{\text{Fuel consumed (g) x calorific value (J/g)}}{\text{Time to boil water (min) x 60}} \text{ kJ/s or Kw}$$

Substitute associated values from tables 4.1 and 4.2 into equation 13 gives the following result:

$$A_1 = 2\pi \text{ x } .268 \text{ x } .09 = 0.152\text{m}^2$$

This fire power means that the stove consumes fuel energy at a rate of 8.598 kilojoules per second. Therefore, its maximum cooking power is 0.4137*8.598 = 3.557KW, which is the power delivered to the pot.

4.3.3. Burning Rate, BR

Burining rate of wood is presented in section 3 as equation 14, stated as:

$$BR = \frac{1}{t}\left[\left(\frac{100 \text{ x } M_{iW}}{100 + X}\right) - \left(\frac{M_C H_C}{H_{WD}}\right)\right]$$

Substitution of the associated parameters from tables 4.1 and 4.2 gives:

$$F = \frac{1}{8 \text{ x } 60}\left[\left(\frac{100 \text{ x } 4}{100 + 0.06}\right) - \left(\frac{0.4 \text{ x } 29000}{4127.25}\right)\right]$$

$$= 0.002083[3.9976 - 2.811]$$

$$= 0.00247\text{kg/s} = 2.47\text{g/s.}$$

4.3.4. Specific Fuel Consumption

In section 3, specific fuel consumption (SFC) is expressed as equation 16:

$$SFC = \left[\frac{M_F(1-X) - 1.5M_C}{M_{iWT}}\right]$$

Substitution of the necessary data from the tables gives the following result.

$$SFC = \left[\frac{3(1 - 0.06) - 1.5 \text{ x } 0.4}{4}\right] = \left[\frac{2.82 - 1.5 \text{ x } 0.4}{4}\right]$$

$$= \frac{2.22}{4} = 0.56 \text{ Kgwood/Kgwater}$$

Specific fuel combustion and burning rates are important metrics used for assessing the fuel consumption rate of a cookstove. The results obtained for this study are better than those obtained by wonder stove, which in essence means, faster cooking time and reduced fuel usage.

4.3.5. Power Consumed for Boiling

Power consumed for boiling is presented in section 3, equation 17:

$$PC = \left[\frac{M_F(1-X) - 1.5M_C}{60t}\right] C_F$$

The substitution of the associated parameters from table 4.1 gives:

$$PC = \left[\frac{2.82 - 1.5 \text{ x } 0.4}{480}\right](4127.25) = 19.09 \text{ kW}$$

DISCUSSION

Thermal efficiency obtained for this study falls under tier 4, according to ISO and WHO performance indicators discussed in section 2.6 of this study. Consequently, readings from table 2.2 show that CO and $PM_{2.5}$ are $4.4g/MJ_d$ and $62mg/MJ_d$ respectively. These values are below those produced by fuels such as Ethanol, LPG, natural gas and electricity. However, they are better than those produced using traditional methods of burning solid biomass fuels. Also, this stove is safer to use and more durable. It is important to note that an increase in tier rating reveals increased efficiency and safety score but decreased CO and PM emissions and durability score. However, a decrease in durability score means the stove becomes durable. These classifications, together with labels on stoves, can help consumers make better decisions on stove purchases to achieve better health benefits.

Previous researchers such as Zube (2010), Sutar *et al.* (2015) and Harsono (2022) show that air flow path confined through the inlet of the combustion chamber reduces mixing of ambient air with combustion gases, which leads to better heat transfer. Accordingly, great efforts were put into the design of air flow path for this study to achieve better fuel combustion, leading to improved thermal efficiency. Jetter *et al.* (2012) conducted an experimental study on TLUD forced draft cookstove and achieved an efficiency of 38% with little emissions of CO and $PM_{2.5}$. In consideration, design of this study is also based on TLUD principle but with higher thermal efficiency. When compared with TSF, Rocket elbow stoves test results show a reduction in fuel saving with a reduction in CO and PM_{25} (Global Alliance for clean cooking, 2018). This study's design was also based on rocket elbow and achieved better thermal efficiency. Results from previous studies state that thermal efficiency increases when scientific principles are employed in the design and fabrication of solid biomass cookstoves (Winiarski, 1982; Geller, 1982; Anderson, 2007; Sweeney, 2017; Tesfaye *et al.*, 2023). The finding of this study resonates with these just mentioned studies, as these principles were employed in the design and fabrication processes, leading to increased thermal efficiency

Improved cookstoves are better alternatives to traditional three-stone fire stoves in addressing pollution and poor efficiency (Pratiti *et al.*, 2020; Pasha *et al.*, 2023). These results run parallel to the results obtained in this study, leading to tier 4 position of the WHO and ISO performance indicators. Studies by Wilson *et al.* (2016), Tesfaye *et al.* (2023) and Jain and Seth (2019) achieved thermal efficiencies of 30%, 30.6% and 35% respectively when scientific principles and materials such as mild steel were in the design and fabrication processes of solid biomass cookstoves. This study employed these processes and achieved thermal efficiency of 41.37%, which is higher than the results obtained by the just mentioned studies. According to Armstrong *et al.* (2021), wonder stove that is widely used in big cities in Sierra Leone is slow in burning charcoal, leading to longer time spent in cooking. This study achieved better specific fuel combustion and burning rates than those obtained by wonder stove, which in essence means, faster cooking time, reduced fuel usage and lower operating cost.

CONCLUSION

Using simple tools, technical and scientific knowledge, together with locally available materials in the design of improved cookstove is directly related to better production efficiency, and leads to easier replication of product. The area provided for primary air to enter the combustion chamber of the stove was sufficient to allow complete combustion of the fuel, which reduces indoor air pollution. Combination of rocket and top-down up draft principles in design of this stove gives it the flexibility of using different fuels, which is a desirable property as less fuel is used. Conversion of biomass, wood, to energy depends on heat and oxygen, as they control the type of thermal conversion processes, thus the design process should incorporate the flow of oxygen into the burning process to enhance thermal efficiency. Gasifier stoves produce very low amount of major air pollutants, like Sulphus Oxides (SO_x) and Nitrous Oxides (NO_x), than direct combustion from traditional cooking methods, thus their use lead to lower emission of these pollutants. This stove is more efficient, safer and more durable than traditional three-stone fire and wonder stove that is widely used in Sierra Leone. Accordingly, it is cheaper, less risky in terms of fire. Fuel efficiency has positive effect in gender equality and economic empowerment, in the sense that, the time saved by women and girl child in reducing collection of wood can be used for studies and other gainful economic activities. An efficient cookstove attracts users of traditional forms of cooking to improved cookstoves that use less fuel and are less polluting, in essence, the use of this stove can result in positive outcome on the environment in the sense that fewer will be cut down, which means reduced deforestation.

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