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DESIGN AND PRODUCTION OF AN IMPROVED COOK STOVE WITH SWINGING COMBUSTION CHAMBER TO ENABLE REFUELING FOR CONTINUOUS OPERATION

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Abstract

Man has been using fire for thousands of years to cook and provide warmth. Studies have shown that, transfer of heat to raw food and cold water is essential for healthier living and taste improvement. The popular wonder stove, which uses charcoal as fuel, is used by most homes in Freetown and big cities in Sierra Leone, while the three stone fire, used widely in rural settings, utilises wood as fuel. Consequently, both heat transfer methods use biomass, a renewable fuel. Wonder stove is more efficient than three stone fire, however, its design makes it difficult to use other forms of fuels. Also, when this stove runs low on fuel, the pot has to be removed for it to be refueled, thereby increasing cooking time and efforts. Review on existing literature revealed that little or no studies exist on cook stoves capable of using multi fuels, proving continuous operation with capacity for fuel adjustment. In order to address this gap in the literature, this study was undertaken by designing and fabricating an improved cook stove with a horizontal swinging combustion chamber, which allows refueling, while the pot is still in position. It runs on both principles of Rocket and Top-Lit Up Draft gasification, capable of using wood, briquettes, charcoal, twigs, wood shavings, etc. Water boiling test together with engineering calculations were performed. The following results were obtained - Burning rate of 4.09 g/s, Specific Fuel Consumption of 0.483Kgwood/Kgwater, Power consumption of 9.947W and a Thermal efficiency of 59.83%. A maximum temperature of 510°C. Therefore, this stove contributes to reduction in deforestation and cooking time.

Key words: Cookstove, Thermal Efficiency, Combustion chamber

1. Introduction

The traditional cookstoves, easy to set up with little operational skill required, came into existence as a result of man's eating and social habits (Mehetre et al., 2017). There are two main types of biomass cookstoves, traditional and Improved Cook stoves (ICS). Improved Cookstove, on the contrary, uses scientific concepts and modern technical skills for better combustion and heat transfer, with the aim of reducing emissions and improving efficiency [Kshirsagar and Kalamkar, 2014]. Cookstoves can burn a variety of solid biomass fuels like crop waste, dung, wood, charcoal, briquettes, pellets, coal, and woodchips (Sweeney, 2017). The most common methods for obtaining energy from solid biomass are gasification, direct burning, pyrolysis, liquefaction, anaerobic absorption, alcoholic fermentation, and transesterification (Ahmad et al., 2019). Due to emissions from inefficient cookstoves using wood, about three million people are exposed to Indoor Air Pollution (IAP) (Bonjour et al., 2013). The reason being, IAP is generated by inefficient combustion of solid fuel, resulting in negative effects on human health (Steenland et al., 2018). Carbon monoxide (CO) and PM_{2.5} (fine particular matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$) are the major emissions

associated with IAP. It is important to note that ICS can minimize the health risks by lowering emissions from cookstoves. A recent study show that ICS can reduce health risks associated with IAP (Pratiti et al., 2020). ICS reduces the burden on women and children associated with fuel collection, in the sense that less fuel wood consumption, thereby helping to reduce deforestation (Mehetre, 2017). Access to affordable and reliable energy services is fundamental to reducing poverty, improving health and promoting economic growth (Nyika, 2020). Thus, availability of clean cookstoves is important to improve health and environmental conditions of people who are still relying on fuel from biomass for daily domestic energy needs.

Notwithstanding these enviable metrics from improved cookstoves, billions of people in developing country, Sierra Leone is no exception, lack access to basic modern energy services. Moreover, little or no access to either electricity or clean cooking facilities are readily available at affordable costs. Aside from few people who use improved cookstoves, majority of the rural households are still using open fire stoves (Tessema and Mekonnen, 2021). The widely used cook stove in Freetown and majority of dwellers in big cities of Sierra Leone, is the Wonder stove, which consists of a combustion chamber made from fired clay and uses charcoal as fuel. The design of this stove makes it difficult for other forms of locally available biomass to be used. Additionally, if the stove runs out of fuel, the pot or cooking container has to be removed in order to refuel it. In essence, there is a pause in the cooking process, which can negatively affect the quality of food to be cooked and can also increase cooking time. In addressing these shortcomings, the impetus for the study was developed. The aim of this study is to design and produce an efficient cookstove, capable of burning different biomass fuels, which can run continuously without a pause in the cooking process to refuel the stove.

2. Literature Review

2.1. Consequences of Open Fire Stoves

Open fire use is an inefficient method for household cooking and heating, as it consumes lot of wood and takes more time to collect such fuel (Jyoti, 2021). The predominant stove used for domestic cooking in rural areas is a three-stone fire with efficiency in the range of 7-15% (Ochieng, 2017). The three stone fire (TSF) is simple to design as it requires no special materials, tools and skills to construct, as shown in figure 2.1. However, its fuel consumption rate and Carbon monoxide (CO) and particulate matter (PM₂₅) are high with low thermal efficiency of about 17% (Chagunda, 2017). Simple design like the built-in (Chullah) stove consumes fuel with minimum radiation loss. Its downside is that, just like the TSF, incomplete combustion with high CO and PM₂₅ with low thermal efficiency of about 29% (Bruce, 2000).



Figure 2.1. Three Stone Biomass cookstove, supporting different pot sizes
Source: Global Alliance for Clean Cookstoves (2018)

Wood is a form of biomass from which useful energy can be extracted, and it is widely available throughout the world. Biomass is a renewable energy resource that is available in the form of crops residues and wastes from plant, animal, forest, metropolitan and food (Bryden, 2005). It is the world's fourth largest energy source for cooking. It is estimated that about 50% of people in developing countries still use biomass from wood, the form of open fire and inefficient stoves for cooking and heating (Lombardi, 2017). Approximately 2.6 billion people, especially in developing countries, rely on traditional cooking methods, using biomass as fuel to meet their cooking needs (Jain, T and Sheth, 2019). Consequently, improved design and production of biomass cookstoves has the potential to improve the lives of about a quarter of the world's population.

2.2. Biomass Cookstoves Design Considerations

In order enhance better performance of cook stove, efforts should be placed on its design and eventual use. This is to achieve better efficiency, burn rate and specific fuel consumption (Saturday et al., 2016). Studies have shown that are challenges to be encountered regarding achievement of high quality product that meets users' budget and preferences, especially those in developing countries (Rao, 1985). With the aim of addressing these challenges, three major factors should be considered when designing a cookstove: Economic, Technical and Social. Social respects depend upon current cultural and local needs and constraints, which are essential for durability of a cookstove. Technical factors include high efficiency, durability, weight, ergonomics, aesthetic, low emission, user's safety. Finally, the economic factor should consider return on investment, cost of production, unit sales cost, affordability and cost of maintenance (Mehetre, 2017; Saturday et al., 2016). It is important to note that, the three factors just mentioned are interdependent, even though they categorized separately as shown in figure 2.2. For example, technical and economic factors, have a relationship with cost, given that cost effectiveness of a stove is usually determined by its technical capabilities.

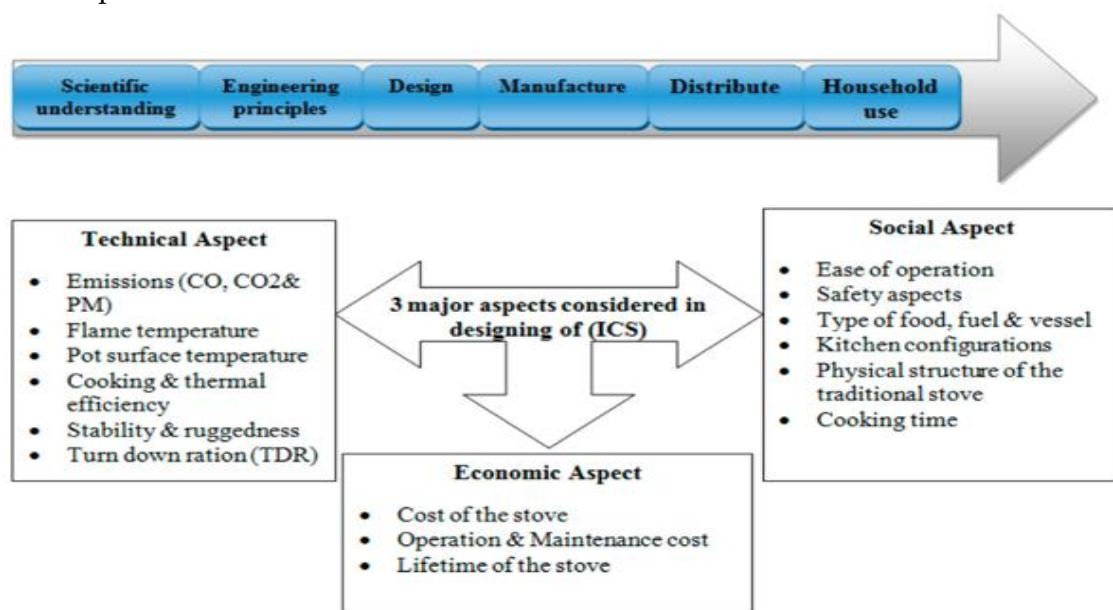


Figure 2.2. Factors considered for cook stove design Source: [Global alliance for clean cookstove, 2018]

2.3. Biomass Combustion, Gasification and Pyrolysis

Gasification, incineration, Digestion and combustion are some of the processes available that are used to convert biomass into useful energy (Jain and Sheth, 2019). Producer gas is a

mixture of the combustible gases - hydrogen, carbon monoxide, and methane and the incombustible gases - carbon dioxide and nitrogen. All of these gases are combustible except nitrogen. In addition, burn rate has a direct relationship with production of CO (Bhattacharya and Salm, 2002). Therefore, burn rate is important in any stove design. Owing to financial hardship, the use of Solid biomass fuels such as wood, animal dung and crop residue are widespread in developing world (Rao, 1985). This is achieved by heating the material at high temperatures ($>700^{\circ}\text{C}$) in the midst of limited amount of oxygen. The resulting gas mixture is called syngas or producer gas which is a fuel (Global alliance for clean cookstove, 2018).

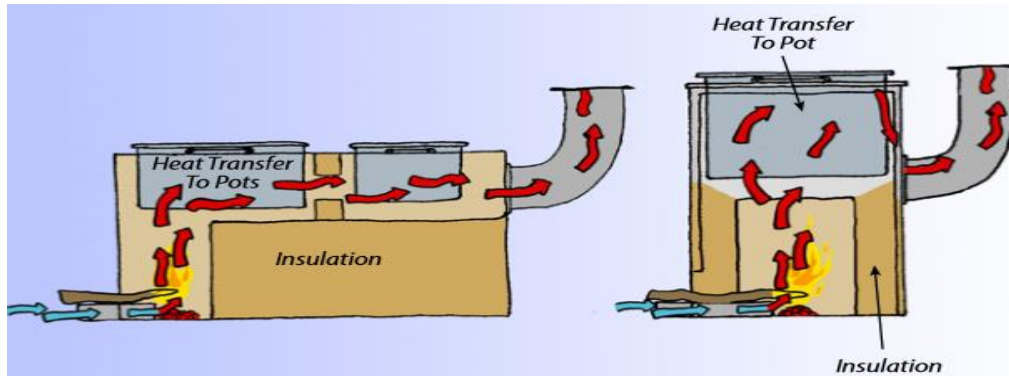


Figure 2.3: Variations of the Rocket Stove heat Transfer Process Source: (Ceruti, 2012)

Heat energy generated in the combustion chamber of the stove is essential during cooking and heating, as that heat is directly transferred to the pot, through convection, for ultimate transfer to the contents in the pot. However, heat is lost through other heat transfer mechanisms, radiation and conduction. Figure 2.3 shows rocket stove operations for cook stoves with single and double pots with chimneys. Combustion is the process through which fuel and air chemically interact at sustainable elevated temperatures. The physical and chemical properties of the fuel, air supply and ambient conditions are determinants of the combustion process. Fluid flow is the movement of fluid, like air, gases and vapours, through a medium under normal pressure. Combustion and heat transfer, the main scientific and engineering principles, required for the design of an improved cook stove with the aim of reducing heat loss conduction, radiation and convection (Mehetre, 2017).



Rocket stove with pot skirt

Hour-Glass design, Wonder Stove

Figure 2.4: Rocket stove Designs Source: GIZ/EnDev (2014)



Figure 2.5: Left, 3-D view of a TLUD Stove in Operation; Right, factors involved in the Process

Source: Anderson et al., (2007).

Burning of biomass fuels involves simultaneous processes. Heating up of the fuel releases the following gases: volatile, pyrolysis, fuel and combustible. The next process involves reaction with these generated gases with oxygen, ignition occurs thereby resulting in visible flame formation. Products from combustion include emissions and exhaust gases (Berhanu et al., 2016). Heat produced in the flame reenters the fuel, which releases more volatile matter and the process continues. After all of the volatile matter is released from the fuel, charcoal remains and reacts with oxygen to produce more heat and combustion products. Figure 2.6 shows a TLUD wood-fuel burning process. Depending on the stove design, moisture content of the fuel, air supply rate, properties of the fuel, heating, temperature of flame can exceed 2000°C (Milind et al., 2014). Figure 2.4: Variations of rocket stove designs, while figure 2.5 shows TLUD design including factors involved in the combustion process.

2.4. Classification of Biomass Cookstoves and Their Properties

Other researchers carried out study on direct combustion of Rocket stove that consumes less fuel with better thermal efficiency and less CO emission, though it requires more maintenance and wood must be thin and dry for better performance (Chica and Perez, 2019). Another form of rocket stove is the mud stove or Parvati that consumes less fuel and cheaper to construct, however, weather and insect damage are some of its weaknesses, coupled with a life span of about two years (Ochieng, 2013). The forced draft stove is light and easy to heat up with low CO emissions and high thermal efficiency when compared with traditional stoves. However, it is expensive and slow to ignite (Coulson and Ferrari, 2019). The Ceramic or Jiko stove burns at high temperature and better insulation and durability than the mud stove, though it is more expensive, difficult to construct and needs high maintenance (Chan et al., 2015). Tryner et al. (2014) opine that the Metallic or vesto stove is portable, light, and quick to heat up with little maintenance needed, however, it is more expensive, prone to rust and with a higher risk of burns to the user. The cement or Mirt stove is cheaper, simpler to design and install but with high fuel consumption and high CO and PM₂₅ emissions rates and low thermal efficiency of about 11% (Bhattacharya et al., 2002). Another stove that is durable with less smoke and CO emission is the hybrid improved stove or Oorja, however, it is expensive and susceptible to rust (Mukunda et al., 2010). Fixed stove or 2-pot is a stove that reduces indoor air pollution by 67%, consumes less fuel with better combustion. However, is it slow to cook with low thermal efficiency of about 20% and needs high maintenance (Urmee and Gyamfi, 2014).

2.5. Efficiency, Burn Rate and Specific Fuel Consumption

(Harsono et al., 2022) used biomass stove fueled by coffee husk. The researchers obtained fuel consumption rate of 0.008kg/minute with a thermal efficiency of 33.15%. ICS are biomass cooking stoves that are designed to maximize thermal and fuel efficiency, operate safely, and emit low levels of pollutants that are damaging to human health [Mehetre, 2017; World Bank, 2020). Clean cooking technologies is a continuous process that has led to design of several types of energy-saving cookstoves for both rural and urban dwellers in developing countries (Anderson and Roth, 2011). One such stove design process is the TLUD technology which can burn almost any solid biomass fuel, including wood pellets, nut shells, crop residues, and animal dung, thereby reducing the depletion of wood resources. Evidence suggests that extensive implementation of cookstoves technology with improvements in energy and combustion providing electricity to remote places (Kshirsagar and Kalamkar, 2020). An improved design resulting in better performance of a gasifier stove can have applications in institutional and institutional settings (Jetter, 2012). Adoption of better designs and good insulating materials can improve thermal efficiency, which reflect on less use of biomass fuel (Jetter, 2012). Consequently, millions of lives could be saved by developing and producing an efficient and affordable cookstove (Waornat, 2001). Therefore, by replacing traditional cook stoves, like three stone fires, with improved cook stoves, can result in appreciable environmental, productivity and health benefits (Heltberg, 2004). Top-lit up-draft (TLUD) micro-gasifier stove design can be used to reduce harmful emissions produced from solid-fuel combustion (Anderson, 2009). A biomass gasifier, like TLUD, consists primarily of a reactor (combustion chamber or container) into which fuel is fed along with a limited air supply (Sustraiawan et al., 2021). In this regard, biomass gasifier cook stoves are based on an improved combustion technology and have better efficiency, consumes less fuels and emits less CO when compared to traditional cook stoves. Gasification is a process that converts materials with carbon content into carbon monoxide, hydrogen, carbon dioxide and methane. Heat for gasification is generated through partial combustion of the feed material (Obi, 2016). Fuel use was decreased and emissions performance improved in laboratory and related benchmarks performance (Mekonnen, 2022). Biomass can be converted into heat and power by adopting appropriate conversion technologies. Sedighi and Salarian (2017) conducted a study on cookstove for sustainable development and found out a negative link between improved cookstove and fuel consumption, that is, the better the stove design, the lower the fuel used. According to (Bielecki and Wingenbach, 2014). Accelerating access to clean cooking can lead to healthier cooking and heating leading to improved health.

It is relevant to note that there are numerous types of cookstoves that have been designed, fabricated and used throughout the world with fascinating metrics regarding fuel consumption efficiency and reduced harmful emissions. However, the reviewed literatures show a paucity of published data on cookstoves that provides continuous operation, capable of using different biomass fuel and an adjustment for fuel consumption. Therefore, this study is carried out to fill the existing gap in the literature regarding this field of study. The aim of this research is to design and produce an improved cookstove, from locally available materials, that uses multi-biomass fuels and capable of refueling while in operation. The design worked on two principles, rocket and top-lit-up-draft (TLUD) which are more efficient than traditional cookstoves. The former principle works on burning biomass placed at 90 degrees to the combustion chamber to produce heat, whilst the latter burns fuel placed in parallel to its combustion chamber. TLUD stoves utilizes a more efficient combustion method by burning gasses from the biomass through a thermos-chemical reactions called gasification and pyrolysis.

3. Materials and Methods

3.1. Materials

In this section the main designs were presented with dimensions to aid reproduction of the stove. Mild steel plates were used on all parts of the stove. Auto Computer Aided Design (AutoCAD) 2022 version was used to produce both 2-Dimensional and 3-Dimensional drawings of the design process. The exploded views of the stove is shown in figure 3.1, whereas table 3.1 gives brief descriptions of the parts. All parts of the stove are made from mild steel with different sizes except for parts C, D, E, F and L, all other parts are made from a 3mm mild steel sheet.

Table 3.1. Brief Explanations of Stove's Parts

	Name Of Part	Brief Explanation
A	Combustion Chamber, CC	Fuel Compartment in which Gasification & pyrolysis occur
B	Swivel Grate	Allowing primary air entrance and exit for ashes
C	Ash Tray	Container for holding ash and little charcoals
D	Frame	structure with three legs and top circular plate, that holds combustion chamber and its parts
E	Handles (2-off)	Meant for lifting and repositioning stove
F	Hinge and rod (2-off)	Combustion chamber swivel mechanisms, attached to left leg, permitting stove to be refueled
G	Side cover of CC	Allows or stops air from entering at the side of stove. Used when fuel is fed vertically; charcoal, wood, twigs, briquettes
H	Bottom Cover OF CC	Swings about the horizontal as regulator of air into the CC
I	Cover for top air entrance	Used, with side and bottom covers, to extinguish fuel in CC
J	Grated fuel adjustor	Used when little fuel is required
K	Frame top with pot rests	Upper circular part of frame, with opening to allow heat exit, that holds 4 pot rests
L	Wood rest	Platform which holds wood that protrudes from stove

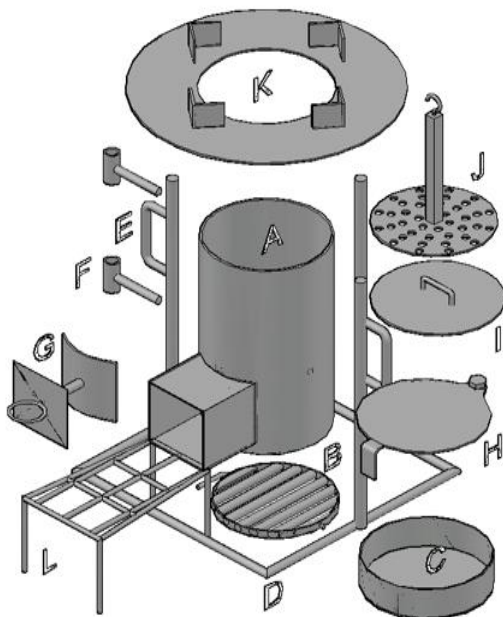


Figure 3.1. Parts of stoves Exploded

The following figures shows 2-D and 3-D views of the stoves, both theoretical and actual figures.

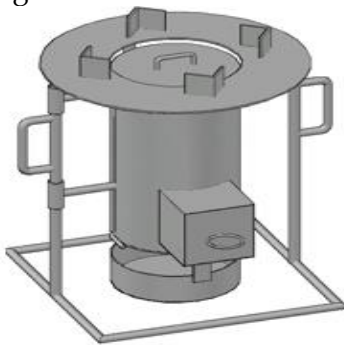


Fig. 3.2: Closed Stove, Non Transparent



Fig. 3.3: Closed Stove, Transparent CC



Fig. 3.4: Position of grate to empty contents of CC

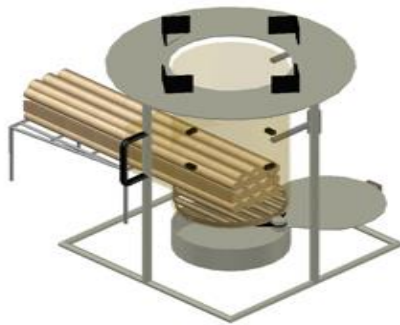


Fig 3.5: Rocket Stove Operation, wood placed horizontally

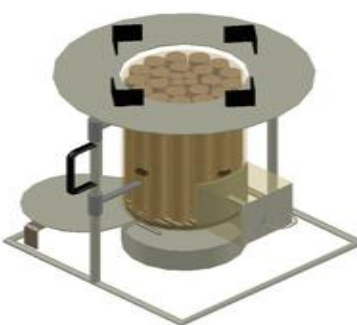


Fig 3.6: top-Lit Up Draft operation, Wood in vertical position

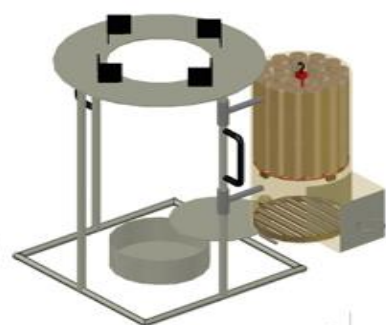


Fig 3.7: CC Swung 90° away from pot rest to Refuel with less wood

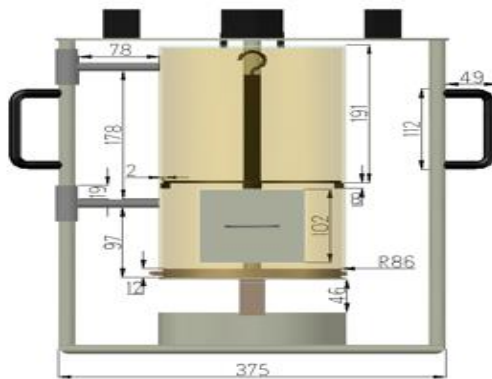


Fig 3.8: Right View with Dimensions

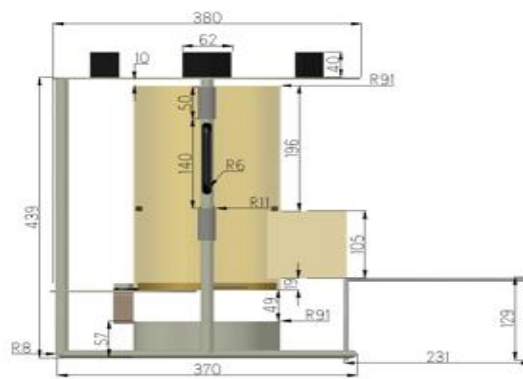


Fig 3.9: Front View with Dimensions

The succeeding figures show the fabricated stove used as TLUD and rocket stove with different biomass fuels. All materials, tools and machines used in the fabrication are locally available in major towns in the country. The stove can also work well if it is fabricated with 1.5 mm mild steel plate, however, it will last half as much as the 3 mm plate used in the design.



Fig. 3.10: Ignition Stage



Fig. 3.11: Used as TLUD



Fig. 3.12: Used as Rocket Stove



Fig. 3.13: Charcoal as Fuel

3.2. Methods and Equations

Primary air entrance, which is essential for burning rate, specific fuel combustion, thermal efficiency and temperature are the main factors considered in the design process. Formulae used to calculate these metrics are provided hereafter. The combustion chamber, reactor, is made of 3 millimeter thick plate, while 16mm diameter rod is used for its three legs. The combustion chamber has an external diameter that is slightly smaller than the diameter of the plate just above it (labelled K in figure 3.1), This is to ensure that maximum amount of heat is transferred to the bottom of the pot before the flame spreads through the sides of the pot. The pot seats are positioned at a distance that will enable smaller diameter of pots to be used on the stove. The distance between fuel bed and pot seat is carefully selected to allow adequate time for complete combustion of fuel particles before the heat hits the bottom of the pot, which enables maximum heat to be transferred.

3.2.1. Area of Air Entrance through Combustion Chamber

Tran and White (1992) posit that the burning rate of a typical fuel wood based on mass loss rate, burning rate, is between 2.92 and $9.8\text{gm}^{-2}\text{s}^{-1}$. Mass of wood burn per second is given as:

$$\dot{m} = 14\dot{m}''A. \quad \text{Equation 3.1}$$

Where A is cross-sectional area of the combustion chamber and \dot{m}'' represents the mass flow rate.

3.2.2. Heat flow across the cylindrical wall of the combustion chamber

According to Fourier's law, heat flow for a hollow cylinder is given as:

$$Q_r = -KA \frac{dT}{dr} \quad \text{Equation 3.2}$$

Where K is the thermal conductivity of the cylindrical material; A is the area of the walls of the cylinder of heating chamber across which heat transfer occurs; and dT/dr is the radial temperature gradient across the walls. For a steady heat flow in which Q_r is independent of r and $T_f > T_i$. Where the subscripts 'I' and 'o' are the inside and outside surfaces of the cylinder respectively. The equation can be integrated and rearranged to give:

$$Q_r = \frac{T_f - T_i}{\frac{1}{2\pi KL} \ln\left(\frac{r_o}{r_i}\right)} = \frac{T_f - T_i}{\left\{ \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi KL} \right\}} \quad \text{Equation 3.2.1}$$

The combustion chamber is a cylindrical mild steel tube of internal radius 88mm and external radius 91mm ('I' and 'o' respectively), and a length of 300mm. It is made from mild steel.

3.2.3. Burning Rate

Burning rate is the amount of fuel used in the experiment with respect to the time. It helps to show whether the stove is effective in utilising fuel. The formula for burning rate of wood is given as:

$$F = \frac{1}{t} \left[\left(\frac{100 \times M_{IW}}{100 + X} \right) - \left(\frac{M_C H_C}{H_{WD}} \right) \right] \quad \text{Equation 3.3}$$

3.2.4. Specific Fuel Consumption

This is the amount of fuel consumed by the stove in bringing to boil the quantity of water required for the experiment. The specific fuel consumption (SFC) is expressed as:

$$SFC = \left[\frac{M_F(1-X) - 1.5M_C}{M_{IWT}} \right] \quad \text{Equation 3.4}$$

3.2.5. 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. Formula is given below.

$$PC = \left[\frac{M_F(1-X) - 1.5M_C}{60t} \right] C_F \dots \dots \dots \text{Equation 3.5}$$

3.2.6. Thermal efficiency of stove

Efficiency is the ratio of the amount of energy given out with respect to the energy used (input) to obtain the output, expressed in percentage. It is expressed as, $\eta = \text{Output/Input} \times 100\%$

$$\eta = \left\{ \frac{S_{HW} \times W_i(T_f - T_i) + L_{EW}(W_i - W_f)}{M_F C_F} \right\} \times 100\% \quad \text{Equation 3.6}$$

3.3. Water Boiling Test

Water Boiling Test is the most popular tests carried out to find out whether a cookstove is both effective and efficiency in burning fuel and ultimately achieving results. The pot and its lid and stove were carefully cleaned and dried avoid extra weights that will affect the results. The bundle of wood to be used as fuel in the experiment was weighed with known moisture content, after which it was introduced through the rectangular opening at the side of the combustion chamber of the stove. The tests were conducted with the air opening on the combustion chamber of the stove fully opened. The stove was ignited and allowed burning of wood to take place until a flame with constant temperature was recorded. Ambient temperature was measured, including the initial temperature of water in the pot before pot and content were placed on the pot stand of the stove and then covered with its lid. The experiment was conducted in an enclosed kitchen environment, at 09:00 in the morning, in Gloucester village, in Freetown. Temperature of water was recorded every 2 minutes until vigorous boiling takes place, wherein that temperature was recorded. Pot and boiled water were weighed and then taken from the stove, and remaining pieces of unburnt wood were removed and flame was quickly extinguished with sand. Smothering the fire with sand saves up to 15% fuel (Owen 1997). The sand is shaken off the wood and charcoal after fire is totally out. The weights of ash, charcoal and remaining wood were weighed and recorded.

4 Analyses and Discussions of Results

4.1.1. Air Entrance of Combustion Chamber

Tran and White (1992) posit that the burning rate of a typical fuel wood based on mass loss rate, burning rate, is between 2.92 and $9.8 \text{ gm}^{-2} \text{ s}^{-1}$. Mass of wood burn per second is given as:

$$\dot{m}_f = 14 \dot{m}'' A. \quad \text{Equation 3.1}$$

Where A is the cross-sectional area of the combustion chamber. Substitute the required data from table 4.1 gives:

$$\dot{m} = 14 \times 9.8 \times \frac{\pi d^2}{4} = 14 \times 9.8 \times \frac{\pi 0.176^2}{4} = 137.2 \times 0.0243 = 3.338 \text{ g s}^{-1} = 3.338 \times 10^{-3} \text{ kgs}^{-1}$$

A typical fuel wood has ultimate analysis by mass for air supply, giving a stoichiometric Air/Fuel ratio of 4.6107 kg air/kg (Ramakrishna (1992). Considering that actual air supply is 20% in excess of stoichiometry, therefore actual Air/Fuel ratio = $(20/100) \times 4.6107 + 4.6107 = 5.5328$ Kg air/Kg fuel. Also mass rate of air is given as:

$$\dot{m}_{\text{air}} = \frac{A}{F_{\text{actual}}} \times \dot{m} = 5.5328 \times \dot{m} = 5.5238 \times 3.338 \times 10^{-3} = 1.846 \times 10^{-2} \text{ kgs}^{-1} \text{ air}$$

Note that, air density = 1.23 Kg m^{-3} and $\dot{m}_{\text{air}} = 1.846 \times 10^{-2} \text{ kgs}^{-1}$

Therefore volume = mass/density = $1.846 \times 10^{-2} \text{ kgs}^{-1} / 1.23 \text{ Kg m}^{-3} = 1.5 \times 10^{-2} \text{ m}^3 \text{ s}^{-1}$

Parker et al. (1969) state that the area of air opening, A_{Air} , is related to the volume flow rate:

$\dot{V}_{\text{air}} = 23.6 A_{\text{Air}} \sqrt{h}$. The height of the air opening of this stove = $h = 100 \text{ mm}$.

$$A_{\text{Air}} = \dot{V}_{\text{air}} / 23.6 \sqrt{h} = (1.5 \times 10^{-2} \text{ m}^3 \text{ s}^{-1}) / 23.6 \sqrt{0.1} = 2.01 \times 10^{-3} \text{ m}^2$$

Air opening is therefore $2.01 \times 10^{-3} \text{ m}^2$. Improved cookstove designs suggest changes to airflow can lead to an increase in efficiency of heat transfer (Ochieng, 2017).

According to Rani et al. (1992), the water boiling test (WBT) is a laboratory test that evaluates stove performance while completing a standard task in a controlled environment to investigate the efficiency of the stove. Data in table 4.1 were used in the calculations of all results obtained, while table 4.2 portrays time and temperature readings taken during the experiment.

Table 4.1. Experimental Data

No	Parameter (Description)	Value
1	Initial mass of water, M_{iWT}	3kg
2	Final mass of water, M_{fWT}	2.75kg
3	Initial Temperature of water, T_i	27°C
4	Final temperature of water, T_f	100°C
5	Mass of empty pot, M_p	2.5 Kg
6	Initial mass of fuel (wood), M_{WFi}	2kg
7	Mass of ash, M_A	0.08kg
8	Mass of charcoal, M_C	0.3kg
9	Final mass of fuel (wood) at the end, M_{WFF}	1.02kg
10	Mass of fuel wood consumed in boiling, M_{WFB}	0.6kg
11	Specific heat capacity of Charcoal, C_C	0.4 kcal/kg
12	Weight of water evaporated during boiling, M_{WEV}	0.25kg
13	Latent heat of evaporation of water, L_{EW}	2260 KJ/Kg
14	Thermal conductivity of mild steel, K	39W/mK
15	Specific heat capacity of pot (Aluminium), C_p	0.9 KJ/Kg°C
16	Specific heat capacity of water, C_W	4.186 KJ/Kg°C
17	Moisture content of fuel wood, X	5%
18	Calorific value of charcoal, H_C	7500kcal/kg
19	Calorific value of fuel (wood), H_{WF}	4127.25 Kcal/Kg
20	Time taken to boil, T	10 minutes

Table 4.2 shows reading of WBT recording during operation. Four readings were taken and recorded every three minutes after the start time, T_1

Table 4.2. Water Boiling Test Results

Fuel used	Time for Boiling					
	Set up time (T_s)	T_1^0 C start	T_2^0 C (3min)	T_3^0 C (3min)	T_4^0 C (3min)	T_5^0 C (1min)
Biomass	5	27	47	65	93	100(10min)

4.1.2. Heat flow across the Cylindrical Wall of the Combustion Chamber, CC

From section 3, Fourier's integrated and rearranged equation for heat flow for a hollow cylinder is given as:

$$Q_r = \frac{T_f - T_i}{\left\{ \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi KL} \right\}} \quad \text{Equation 3.2}$$

The combustion chamber is a cylindrical mild steel tube of internal radius 88mm and external radius 91mm ('I' and 'o' respectively), and a length of 300mm. it is made from mild steel. K for mild steel = 3939W/mK, $T_f = 510^\circ$ and $T_i = 30^\circ$

Substitution of the associated parameters from table 4.1 gives:

$$Q_r = \frac{510-30}{\frac{1}{2 \times 3.142 \times 0.3 \times 39} \ln\left(\frac{91}{88}\right)} = \frac{480}{\frac{1}{73.523} \times 0.0335} = \frac{480}{\frac{0.0335}{0.0136}} = \frac{480}{2.463} = 194.884W$$

It is important to note that if the wall of the combustion chamber is thicker than 3mm, whilst holding all other parameters constant, the heat transfer will reduce. This shows an inverse relationship between heat transfer and wall thickness of CC. Additionally, there is also an inverse relationship between length of reactor and heat transfer, that is, the longer the length of the CC, the lower the heat transfer.

4.1.3. Burning Rate

Burning rate of wood is given as:

$$F = \frac{1}{t} \left[\left(\frac{100 \times M_{iW}}{100 + X} \right) - \left(\frac{M_{cHc}}{H_{WD}} \right) \right] \quad \text{Equation 3.3}$$

Substitution of the associated parameters from table 4.1 gives:

$$F = \frac{1}{10 \times 60} \left[\left(\frac{100 \times 3}{100 + 0.05} \right) - \left(\frac{0.3 \times 7500}{4127.25} \right) \right] = 0.0017[2.454] = 0.00409\text{kg/s} = 4.09\text{g/s}$$

4.1.4. Specific Fuel Consumption

The specific fuel consumption (SFC) is expressed as:

$$\text{SFC} = \left[\frac{M_F(1-X) - 1.5M_C}{M_{iWT}} \right] \quad \text{Equation 3.4}$$

Substitution of the necessary data from table 4.1 gives the following result.

$$\text{SFC} = \left[\frac{2(1 - 0.05) - 1.5 \times 0.3}{3} \right] = \left[\frac{2(1 - 0.05) - 1.5 \times 0.3}{3} \right] = \frac{1.45}{3} = 0.483 \text{ Kgwood/Kgwater}$$

4.1.5. Power Consumed for Boiling

$$\text{PC} = \left[\frac{M_F(1-X) - 1.5M_C}{60t} \right] C_F \quad \text{Equation 3.5}$$

The substitution of the associated parameters from table 4.1 result in:

$$PC = \left\{ \frac{1.45}{60 \times 10} \right\} \times 4127.25 = 0.0024 \times 4127.25 = 9.947W$$

4.1.6. Thermal efficiency of stove

$$\eta = \frac{S_{HW} \times W_i(T_f - T_i) + L_{EW}(W_i - W_f)}{M_f C_f} \quad \text{Equation 3.6}$$

The required data from table 4.1 were substituted in the above equation which result in:

$$\text{Thermal Efficiency} = \frac{4.186 \times 3(100 - 27) + 2260(3 - 2.75)}{0.6 \times 4127.25} = \frac{1,481.734}{2476.35} = 59.83\%$$

4.2. Discussion

Obi et al. [43] developed a TLUD stove and results show better performance than traditional stoves. Tryher et al. (2014) investigated the effect of fuel type on efficiency and measured a thermal efficiency of 42%. Mekonnen (2022) reported an efficiency of 32% and specific fuel consumption of 43%, which are lower than results obtained for this study. A thermal efficiencies, from three stone fire and rocket stoves, of 14% and 32% respectively were obtained by Sustriawan et al. (2021) which is lower than the one obtained from this study. When compared to study by Harsono et al. (2022), their fuel consumption rate was lower than that obtained by this study, however, their thermal efficiency was lower, 33.15%. Interesting to note is that better cookstove design leads better thermal efficiency and less fuel consumption (Chica and Perez, 2019; Sedighi and Salarian, 2017). Specific fuel consumption results obtained for this research is lower but with higher thermal efficiency than that of a cook stove designed by (Saturday et al., 2016).

In another study, the ceramic Jiko stove in Kenya saved 20–50% fuel relative to a three-stone stove, Coulson and Ferrari (2019), whereas this stove saved an estimated 54% compared to three stone fire. MacCarty et al. (2022) find that fuel use would be reduced by 33% relative to the open fire stove. Additionally, studies on improved cookstoves in Gambia, Guatemala and China registered fuel saving of 40%, 39% and 40.1 respectively (Bielecki and Wingenbach, 2014). Since this stove consumed less fuel compared to other wood stoves used in Sierra Leone, it is sensible to suggest that the less wood consumed as fuel, the less CO emission and deforestation. These results are reflective of the requirement of World Bank (2020) regarding better access to clean cooking. The impact of fuel savings on CO₂ will be mirrored positively, given that less wood consumed will result in less wood cut from forest, resulting in less CO pollution.

4.3. Conclusion

- Three stone fire stoves are still the preferred method used by most cookers in rural Sierra Leone, while the wonder stove is the preferred option for most users in big cities in the country. Burning rate and specific fuel consumption for the stove designed for this study is lower than that those for three stone fire and wonder stoves.
- Burning rate registered for this study is lower than results obtained from literature reviewed of lots of improved cook stoves used elsewhere. Moreover, the flexibility of this stove regarding its ability to use various solid biomass fuel, continuous operation and ease of use are attractive factors for users with regard to faster and less expensive mode of cooking.
- A stove with better thermal efficiency and lower burn rate, as this one, is better for the environment with positive financial results on users, in the sense that less trees would be cut down (a reduction in deforestation) and less money spent on

purchasing solid biomass fuel. Therefore design and production of improved cook stoves are one of the solutions required to aid in reducing the challenges faced with inefficient biomass cookstoves.

- Results show that the smaller the pieces of wood to be used as fuel, both rocket and TLUD, the faster the cook time and less smoke produced. Consequently, solid fuel to be used on this stove, should be of low moisture content and cut into smaller pieces for better performance.
- Given that this stove can be used as rocket and Top-Lit Up Draft, makes it suitable for different solid biomass fuels to be used, nuts, shells, wood, charcoal, agricultural wastes. The technological improvement done on this design makes it an attractive option regarding less efforts required from ignition to end of operation. Additionally, these results mirror government's aspirations regarding sustainable and efficient use of wastes and solid biomass leading to a reduction in deforestation.

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