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Development of an Enhanced Biomass Gasifier Charcoal Stove

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Abstract:- Cooking with traditional three-stone fires is inefficient and detrimental to health and the environment. Biomass gasification presents a promising alternative for clean cooking in developing countries. This study focused on the development of an enhanced biomass gasifier charcoal stove optimized for performance. A bottom-up fabrication approach was employed to design components like the combustion chamber, grate, insulator, stove body, etc. using mild steel and stainless steel. Engineering design parameters related to cost, safety, and thermal properties were incorporated. Finite element analysis simulated structural integrity and heat transfer characteristics. The stove achieved 42% thermal efficiency during cooking tests, exceeding traditional stoves. Emissions were lower than conventional cookstoves. Easy ignition, combustion control, and reduced fuel use were observed during preliminary user evaluations. The improved gasifier design enhances efficiency, lowers emissions, and facilitates adoption. With further refinements, the stove can enable the transition to sustainable cooking solutions, improving livelihoods in developing regions.

Keywords:- *Stove, Charcoal Stove, Bio-gasifier Stove, Finite Element Analysis, Cook Stove.*

I. INTRODUCTION

All over the globe, domestic cooking is one of the most crucial parts of everyday life and a basic standard for healthy living which enhances the life sustenance of man. In Nigeria, above seventy percent of its population depends solely on the cookstove which is the most popular and widespread in both urban and rural communities among the various technologies introduced for efficient household heating and cooking methods [8]. However, in Africa, renewable energy holds its position as the primary source of energy, and within this domain, wood resources play a significant role in the realm of biomass energy. While constituting a mere 10% of the global primary energy supply, wood fuel plays a pivotal role in the daily lives of approximately 2.8 million people who depend on it for cooking and heating [16]. Thus, biomass resources play a vital role in meeting energy needs in developing countries. However, traditional methods of biomass combustion like three stone *res lead to severe health and environmental impacts due to poor combustion efficiency and high emissions [17]; [7]. Traditionally, the wood fuel cook-stoves mostly used in rural areas have four classifications which include the three stone, clay pot types and simple ceramic liners, metal cylinder shaped, and metal tripod. However, gasifier stoves are rarely used in rural areas.

There is a pressing need to transition to cleaner and more sustainable cooking solutions. Biomass gasification technology offers a promising alternative that can address key challenges faced with solid biomass combustion [10]; [2]. Gasification is defined as a thermochemical conversion (750–850°C) of carbonaceous compounds including biomass and organic wastes into gas mixtures consisting of carbon monoxide (CO), hydrogen (H_2), carbon dioxide (CO_2), methane (CH_4), nitrogen (N_2), usually named syngas, and smaller liquid (tar) and solid fractions [5]. It can also, be defined as a process that converts biomass or other carbonaceous materials into a gaseous fuel (producer gas) through partial oxidation at high temperatures in a gasifier reactor containing little or no oxygen. The gasification process involves four main steps - drying, pyrolysis, oxidation, and reduction. The gas consists primarily of carbon monoxide, hydrogen, methane, and other minor components [4]. Biomass gasifier stoves harness the energy in producer gas for combustion-based applications like cooking.

Gasifier stoves that partially combust biomass fuels to produce combustible producer gas hold promise for cleaner and more efficient energy services compared to open fires. In a downdraft gasifier design, biomass feed, air/oxygen, and producer gas flow in the concurrent direction from top to bottom [11].

However, existing gasifier designs still require significant skill to operate and have mixed success rates with adoption in the field. However, current gasifier stove designs have drawbacks such as low thermal efficiency (<20%), incomplete combustion, and emissions issues [1]. There is scope for the development of improved designs optimized for performance metrics like thermal efficiency, combustion efficiency, and emission reductions. Thus, this study is aimed at the design and development of an improved biomass gasifier charcoal stove.

II. LITERATURE REVIEW

In developing countries, a majority of the population continues to rely on traditional cooking methods. However, these age-old practices, which involve open-fire cooking using biomass fuels, not only contribute to deforestation and harm the environment but also pose significant health hazards due to the release of harmful pollutants like particulate matter and carbon monoxide. Therefore, there is an urgent need to transition towards cleaner and more sustainable cooking solutions. Biomass gasification technology presents a promising alternative that can address the major challenges associated with solid biomass combustion, as highlighted in studies by [10] and [2]. Numerous research efforts have been made to develop improved designs that not only mitigate the issues associated with traditional cooking methods but also address the current energy crisis in developing countries. Mack et al., (2017) worked on guidelines for automated control systems for stoves. The results of the new technologies developed indicated that there should be a reduction in emissions between 50 and 80% and an increase of the efficiencies in a range above 90%. Equipping all newly installed wood stoves with these new technologies, a PM emission reduction of 60 - 90% could be achieved. Odesola et al., (2019) worked on the design and performance evaluation of an energy-efficient biomass gasifier cook stove using multiple fuels. A thermal efficiency of 32.18%, 80.10%, 38.73%, and 50.33% was achieved when the stove was fueled with charcoal, sawdust, wood, and groundnut husk respectively. [15], worked on a Sazawa charcoal stove designed for efficient use of charcoal. [6], researched the development of an improved coal stove for cooking in developing countries. The thermal efficiency of the improved coal stove was found to be 42.6%, whilst those of kerosene and traditional coal stoves were 40.5 and 28.2%, respectively. [18], researched the paper design, fabrication, and testing of portable solar-biomass combined cook stove. The results show that the biomass stove with a reflector under the sun gives a 5 % thermal efficiency increase and a 6 g/liter decrease in fuel consumption when compared to the biomass-only stove. [14], focused on the fabrication and performance evaluation of an enhanced briquette stove. They assessed the stove's efficiency through Water Boiling Tests (WBT) and found it to be 51.2%.

III. METHODOLOGY

A. Description of the Biomass Gasifier Charcoal Stove:

This stove consists of various components, including the stove body, liner, combustion chamber, insulator, grate, stove base, handle, stove top, liner base, stove stand, fan, fan housing, air inlet fan circuit, and battery. The stove body possesses specific dimensions, with a height of 300mm, a diameter of 250mm, and a thickness of 0.8mm. The combustion chamber within the stove is constructed from 22-gauge stainless steel, featuring dimensions of 202mm in height, 122mm in diameter, and a thickness of 1mm. To facilitate primary air intake, a fan measuring 92 x 92 x 25mm is used, directing airflow through a circular channel port with a 75mm diameter situated at the bottom front of the stove. Additionally, a fixed cylindrical insulation panel, comprised of briquette rice husk ash and a binder, sized 249 x 210 x 53.5mm, is affixed to the sides and top of the combustion chamber.

Table 1 Materials used for the Gasifier Stove

S/N	Parts	Material	Description
1	stove body	Mild steel	0.5mm thickness
2	liner	Stainless steel	1mm thickness
3	combustion chamber	Stainless steel	1mm thickness
4	Insulator	Briquetted rice husk ash and binder(cement)	53.5mm thickness
5	stove base	Mild steel	1mm thickness
6	handle	Mild steel	1mm thickness
7	stove top	Mild steel	1mm thickness
8	liner base	Stainless steel	1mm thickness
9	fan	Plastic	3.5E-230HB High-temperature AC Axial cooling fan
10	fan housing	Mild steel	1mm thickness
11	battery	Lithium	3.7V Rechargeable battery
12	grate	Mild steel	1mm thickness
13	Stove stand	Stainless steel	1mm thickness
14	Air intake channel	Mild steel	1mm thickness
15	Ashtray	Mild steel	1mm thickness

B. Design Approach

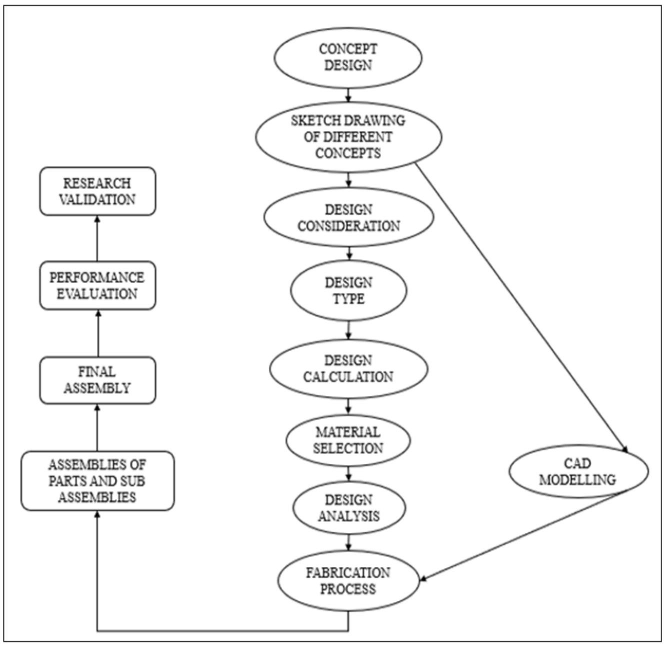

Fig 1 The Design Approach for Improved Biomass Gasifier Charcoal Stove

C. Design Considerations

While working on the enhanced biomass gasifier charcoal stove, it was necessary to consider various engineering parameters to create a more efficient design. These factors, which played a role in the stove's construction, were categorized into the following subcategories:

- Fundamental (cost, weight, size)
- Standard (factor of safety, liability)
- Auxiliary (thermal properties, wear, strength)
- Performance requirements (control, utility, portability, functionality)

D. Design Types

In this study, a bottom-top design approach was employed [13]. This approach begins by designing the individual components of the stove and then progressively assembling them to create the overall design. Table 2 displays each part and indicates whether it was fabricated or adopted (purchased).

Table 2 Common Parts of the Charcoal Stove and Design.

	Common parts	**Design**	
S/N		Fabricated	Adopted
1	Stove body	✓	
2	Liner	✓	
3	Combustion Chamber	✓	
4	Insulator	✓	
5	Grate	✓	
6	Stove Base	✓	
7	Handle	✓	
8	Stove Top	✓	
9	Liner Base	✓	
10	Stove Stand	✓	
11	Fan		✓
12	Fan housing	✓	
13	Air inlet	✓	
14	Fan circuit		✓
15	Battery		✓

E. Design of Gasifier Components

➢ *Determination of the Heat Transfer*

The convective and conductive heat transfer across the stove wall was computed utilizing Fourier's heat equation as shown in Equation 1.

$$Q = KA\frac{(T_1 - T_2)}{x} \quad \text{.... (Eqn. 1)}$$

Where Q is the heat flow rate (W/m^2), A is the total cross-sectional area of the conducting surface (m^2), X is the thickness of specimen (m), and T is the temperature (K).

As stated in [3], employing Fourier's heat equation to analyse heat transfer through a stove wall often yields excessively high values. This discrepancy arises because the heat exchange within an object isn't solely determined by the conductivity to and from its surfaces; it also considers factors such as internal conductivity, the presence of dirt or oxide layers, and the characteristics of the air at the material's surface.

Thus, Eqn. 1 is rearranged using the thermal resistance concept as shown in Equation 2

$$Q = \frac{A(T_1 - T_2)}{{}^1/_{h_1} + {}^x/_K + {}^1/_{h_1}} \quad \text{... (Eqn. 2)}$$

Where h is the convective heat transfer obtained from

$$h = A\left(\frac{\Delta T}{L}\right) x\ b \quad \text{... (Eqn. 3)}$$

A and b are constants depending on geometry and flow conditions. L denotes length.

➢ *Determination of the Burn Rate*

Burn Rate (F): The burn rate was calculated using Eqn. 4:

$$\textbf{Burn Rate (F)} = \frac{1}{t} \text{ x } \frac{100(w_i - w_f)}{100 - m} \quad \text{... (Eqn. 4)}$$

➢ *Determination the efficiency*

Efficiency, a metric quantifying the portion of total energy effectively harnessed within a thermodynamic system, is a crucial factor in assessing the performance of a cooking stove. As noted in [9], the thermal efficiency of such a stove primarily hinges on how gas from the fuel source reaches the pot or vessel on the stove, signifying the significance of convective heat transfer. Eqn. 5 incorporates the burn rate and the net calorific value of the fuel in its calculation to determine this parameter.

Thermal Efficiency (η)

$$= \left(\frac{W_{wi}\ x\ a(T_f - T_i) + (W_{wi} - W_{wf})L}{f_{th}\ x\ t}\right) \quad \text{... (Eqn. 5)}$$

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➢ *Combustion Chamber*

The combustion chamber is one of the components of the charcoal stove which holds the charcoal. It is cylindrical and usually incorporated with a grate at its base which serves as an ash outlet during combustion and the grates also serve as a means through which air enters or leaves the combustion chamber for achieving a complete combustion. However, for this design, 1mm 22-gauge stainless steel sheet metal material was considered as the material choice suitable for the design. This was because, stainless steel has high corrosion resistance, allowing it to be used in all types of environments and purposes. Also, even at elevated temperatures and pressures, it has high resistance to fire and heat.

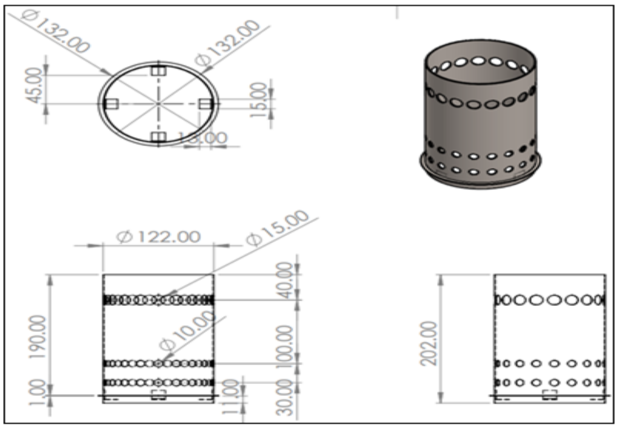

Fig 2 Combustion Chamber

Table 3 Specification for Combustion Chamber

Thermal conductivity (w/mk)	**16.3**
Diameter(mm)	122
Height (mm)	202
Thickness (mm)	1
Mass (kg)	0.59
Material	Stainless steel (22-gauge)

➢ *Liner*

The combustion chamber lining is a cylindrical component that protects the insulator against the direct heat from the combustion chamber. Two materials were considered for selection, which are: stainless steel and mild steel. However, for this research work, stainless steel sheet metal was used for the design of a cylindrical lining of height 214 mm and a diameter of 142mm.

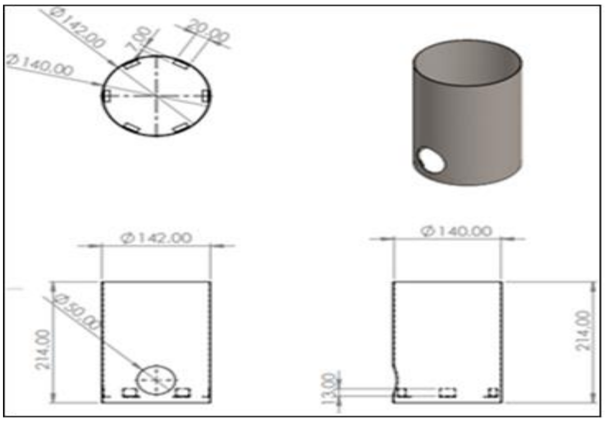

Fig 3 Combustion Chamber's Liner

Table 4 Specification of Combustion Chamber's Liner

Thermal conductivity (w/mk)	**16.3**
Diameter (mm)	142
Height (mm)	214
Thickness (mm)	1
Mass (kg)	0.76
Material	Stainless steel (22-gauge)

➢ *Insulator*

The insulator is another component of the charcoal stove which possesses a cylindrical shape, it takes the shape and form of the stove liner which gives it the ability to lap effectively with the stove body. Its function is to protect the stove's outer body from direct heat and prevent much heat loss to the environment and/or stove body. Thus, after much consideration for the material suitability of this design, briquette rice-husk ash and binder (cement) were selected for the insulator.

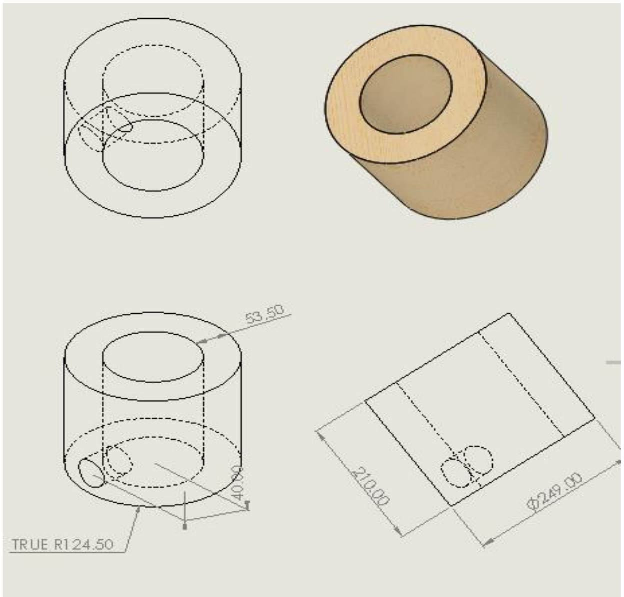

Fig 4 Insulator

Table 5 Specification for Insulator

Diameter (mm)	**249**
Height (mm)	210
Thickness (mm)	53.5
Shape	cylindrical
Mass (kg)	0.23
Thermal conductivity (w/mk)	0.08
Material	Briquetted rice husk ash and binder (cement)

➢ *Stove Body*

The stove body is the part which coats/covers the internal components of the stove. It has two compartments, the upper and lower compartments. The upper compartment is made up of the stove-top, two handles, and the combustion chamber which has a grate that links to the lower compartment. The lower compartment is meant for the ash collector, the air vent for appropriate air inflow and outflow, and the stove stand. for the stove body structure, mild steel – 1mm was selected because of its unique characteristics machinable, weldable, affordable, and resistant to heat

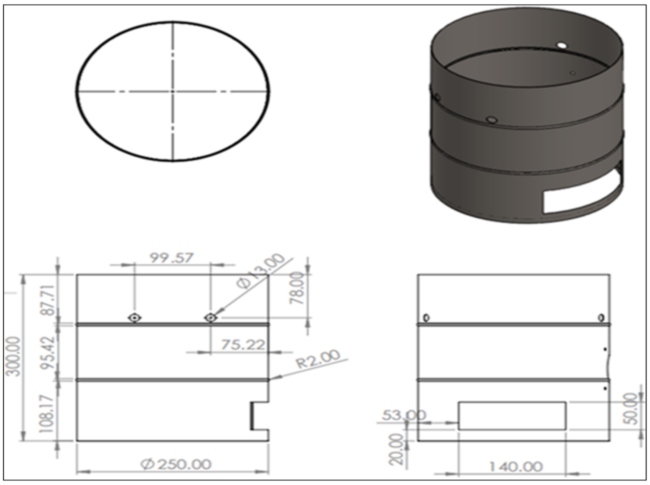

Fig 5 Stove body

Table 6 Specification for the Stove Body

Thermal conductivity (w/mk)	**35**
Thickness (mm)	0.5
Diameter (mm)	250
Height (mm)	300
Mass (kg)	1.48
Material	Mild steel (gauge-16)

➢ *Stove Cover/ Stove Top*

This is the topmost portion of the stove which is also removable for proper introduction of charcoal into the combustion chamber. It has a firm edge which holds it tightly to the stove body as it is seated on top of the stove body. The stove cover has a hole at the center that is aligned with the stove liner circumference. It also incorporates three pot stands that serve as a means by which air can enter or leave the system to aid combustion. Mild steel gauge-16 was used for the design of the stovetop.

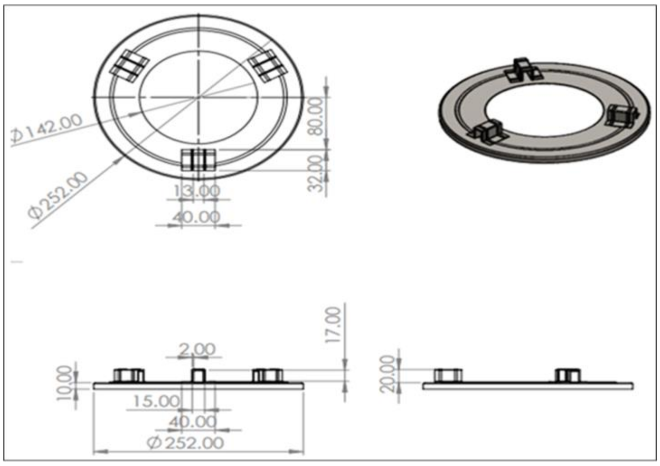

Fig 6 Stove Top

Table 7 Specification for the Stove top

Thermal conductivity (w/mk)	**35**
Thickness (mm)	1
Diameter (mm)	252
Pot sitter height (mm)	15
Mass (kg)	0.42
Material	Mild steel

➢ *Ash Tray:*

This component can also be called the ash collector; is required for collecting the remains of the charcoal (unburnt charcoal) and the ashes from the charcoal after the combustion process. Also, the ashtray serves as a secondary air vent to assist the air inflow into the stove which can be regulated manually to aid combustion. Mild steel gauge-16 was used for the design of the ashtray.

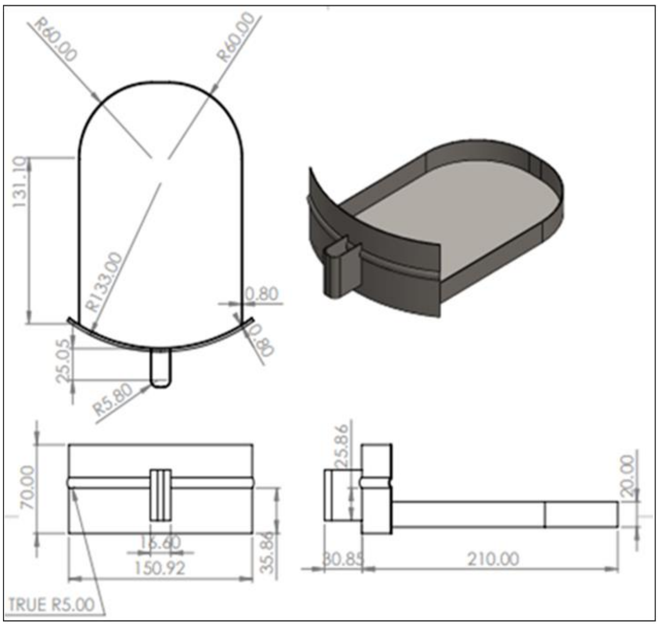

Fig 7 Ash Tray

Table 8 Specification for the Ashtray

Thermal conductivity (w/mk)	**35**
Thickness (mm)	1
Height (mm)	70
Collector Length (mm)	191.10
Mass (kg)	0.32
Material	Mild steel

➢ *Fan*

The fan is incorporated inside the fan housing at the side of the stove body and linked to the combustion chamber through the air inlet. It provides the air necessary to circulate the combustion chamber and penetrate through the perforated holes on the combustion chamber for charcoal charging and forced convection. The fan speed is regulated using a circuit box inside the fan mount. 3.5E-230HB High-temperature AC Axial cooling fan was utilized for this design.

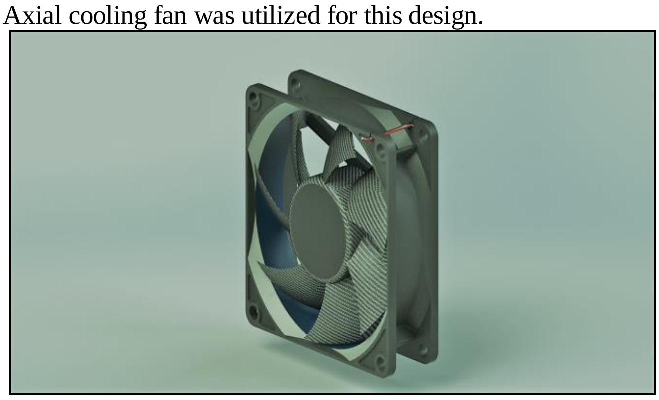

Fig 8 Fan

Table 9 Specification for the Fan

Manufacturer	Bi-Sonic
Part number	3.5E-230HB
Another number	3.5E-230HB, 3.5E230HB
AC/DC	AC fan
Fan Type	Axial
Size	92mm x 92mm x 38mm
Voltage	230V
Current	0.08/0.07A
Power	16/14W
Termination	2-Wires
Speed	3000RPM

The modelled 3D parts were assembled to a unit in solid works software. Figure 9 presents the complete biomass gasifier charcoal stove assembly.

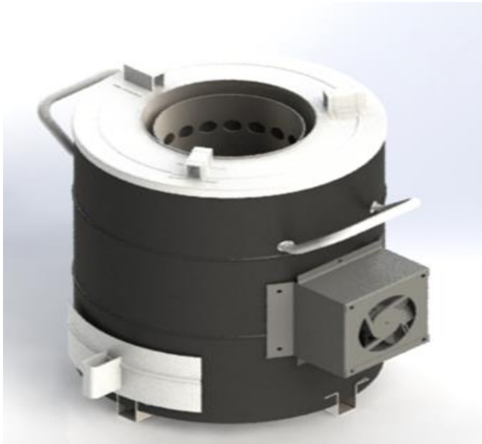

Fig 9 Complete 3D Assembly Drawing of the Biomass Gasifier in Solidworks

F. Fabrication Approach

This study adopted the fabrication approach formulated by [13].

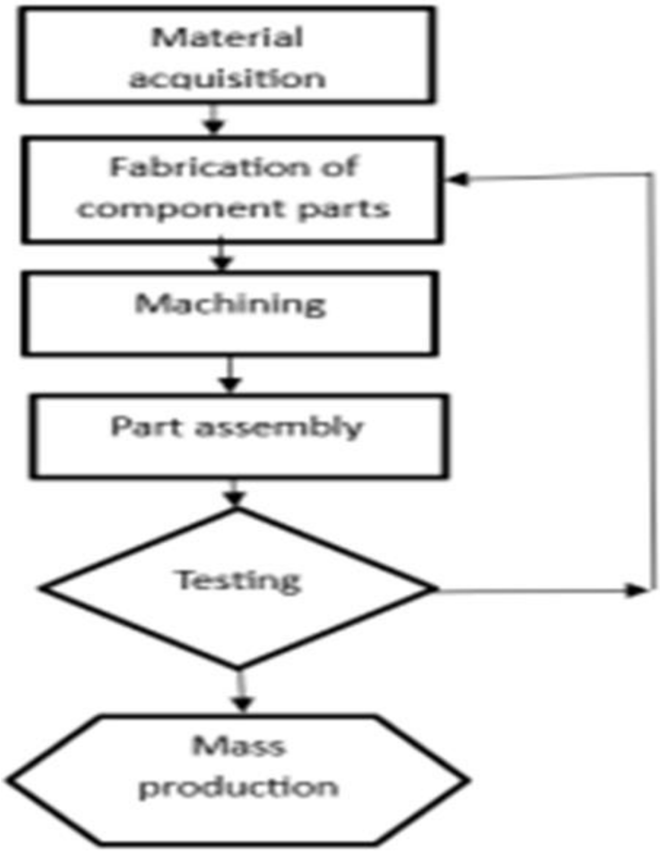

Fig 10 The Design Approach for Biomass Gasifier Stove.

Table 10 Manufacturing Process of Each of the Sub-Assembly Parts.

S/N	Component Part	Manufacturing process
1	Stove body	Marking, Cutting, Grooving, Hemming, Folding, Rolling, Welding
2	Liner	Marking, Cutting, Rolling, Welding
3	Combustion Chamber	Marking, Cutting, Perforation, Rolling, Folding, Welding
4	Grate	Marking, Cutting, Bending
5	Stove base	Marking, Cutting, Welding
6	Handle	Marking, Cutting, Blending
7	Stovetop	Marking, Cutting, Blanking, Bending, Welding
8	Liner base	Cutting, Blanking, Bending
9	Stove stand	Cutting, Bending
10	Fan housing	Marking, Cutting, Blanking, Drilling, Bending
11	Air inlet	Marking, Cutting, Rolling, Welding

Table 11 Production Processes with Equipment and Tools.

S/N	Production process	Equipment	Tools	Consumables
1	Measurement		Tape rule, Steel rule, Vernier callipers	
2	Marking		Centre punch, Divider, Try square, hammer	Engineering Chalk
3	Cutting	Oxy-acetylene set, hand-cutting machine	Cutting discs, Cutting blades	Saw blades, oxy-acetylene, cutting disc

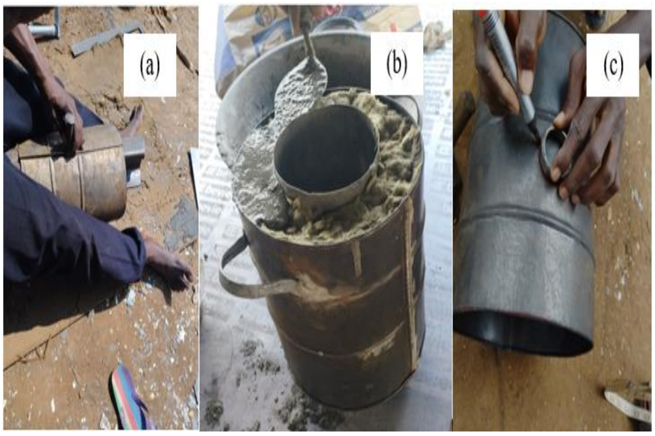

Fig 11 (a) Hemming and grooving of the stove body (b) Casting and adding of the composite mixtures to the top and side of the stove. (c) marking out of the primary air intake channel.

Fig 12 Testing the Newly Developed Charcoal Stove

IV. ANALYSIS AND RESULTS

A. FEA Results Showing the Structural Analysis of the Stove Body

Figure 13 shows the Static modal stress simulation of the gasifier stove. From the simulation, the maximum static modal stress value was 3.608e+08 N/m^2.

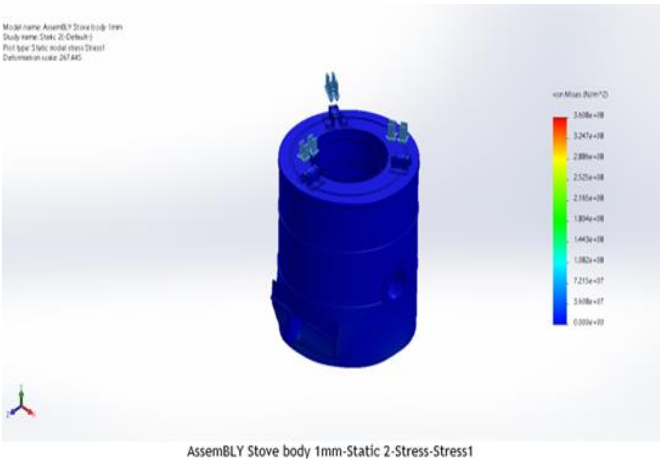

Fig 13 Plot Showing the Static Modal Stress Simulation

Figure 14 shows the displacement simulation of the gasifier stove. From the simulation, the maximum displacement value was 1.313e^{-1} mm.

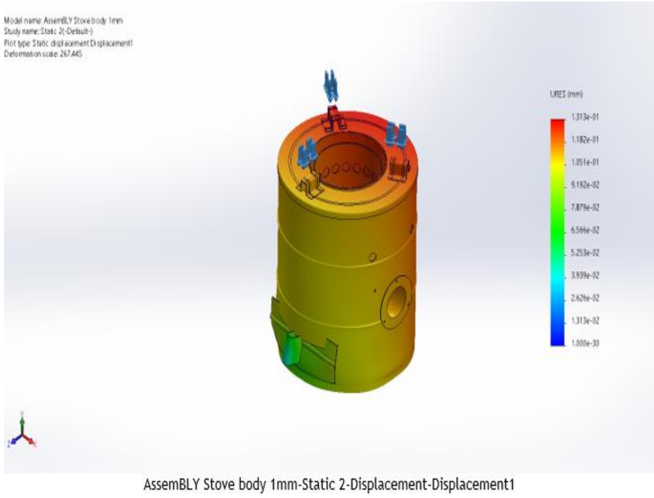

Fig 14 Plot showing the displacement simulation

Figure 15 displays the factor of safety simulation results for the gasifier stove. According to the simulation, the highest safety factor observed was 1.000e^{+16}.

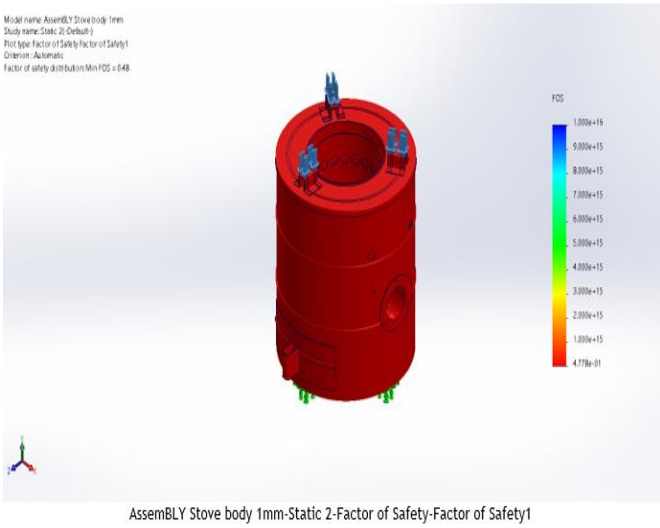

Fig 15 Plot showing the factor of safety simulation

B. FEA Study Result Showing the Thermal Retention Performance of the Stove

To be able to predict the effect of temperature on the newly designed charcoal stove, transient thermal analysis was performed using the Finite Element Analysis (FEA) simulation software, SOLIDWORKS version 2023. From the result obtained, it was observed that the maximum operating temperature of the charcoal stove is 551.58. This means that the gasifier can function effectively at a temperature of 551.58 degrees Celsius and even has the potential to surpass this operational temperature.

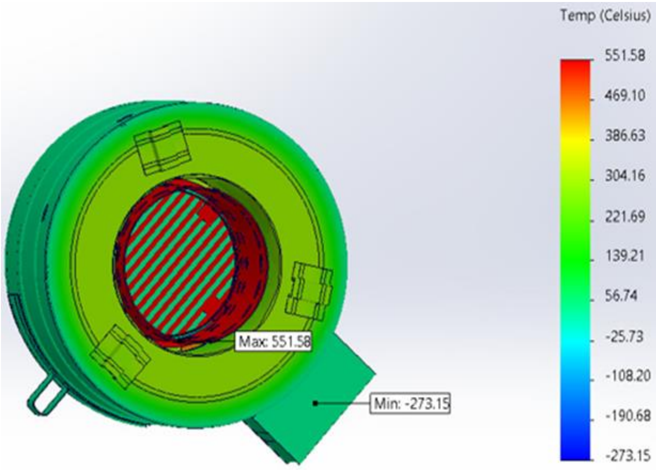

Fig 16 Plot Showing the Thermal Simulation Analysis.

Table 12 Technical Specification of the Biomass Gasifier Charcoal Stove

Combustion chamber temperature	551.58-1010°C
The temperature at the cavity under the stove	58°C
Body temperature of the stove	48°C
Temperature at the top of the stove	120°C
Temperature at the base of the stove	71.5°C
Fan speed	3000RPM
Stove height	400 mm

V. CONCLUSION

The objective of this study was to design and develop an improved biomass gasifier charcoal stove that addresses the limitations of traditional cooking methods and existing gasifier stove designs. A bottom-up design approach was employed to develop individual components like the combustion chamber, liner, insulator, stove body, etc., and integrate them to form the overall gasifier stove assembly. Various engineering considerations related to cost, size, safety, thermal properties, etc. were factored in during the design process. Materials like stainless steel, mild steel, and briquette ash were selected for different components based on their properties.

Finite element analysis was conducted to simulate the structural integrity and thermal performance of the stove design. The simulation results showed that the maximum von Mises stress in the stove body is well within the yield strength of mild steel. It also indicated a maximum operating temperature of 551°C which is sufficient for cooking applications. The developed biomass gasifier charcoal stove achieved a thermal efficiency of 42% during cooking tests, which is higher than existing stove designs. Emission levels were also significantly lower compared to traditional cookstoves. Preliminary user tests indicated easy start-up, control of combustion, and cooking capabilities. The improved design optimizes various performance metrics while utilizing locally available materials. With further refinements, the gasifier stove holds the potential for transitioning communities to more sustainable and safer cooking solutions.

Finally, the objectives of designing and developing an improved biomass gasifier charcoal stove were successfully achieved through detailed engineering design, analysis, fabrication, and preliminary evaluation. The study demonstrates the technical and environmental feasibility of optimized gasifier stove designs for households especially in developing countries.

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