Nigerian Journal of Tropical Engineering
Vol. 18 No. 3 |ISSN: 1595-5397| Dec. 2024 DOI: 10.59081/njte.18.3.009

STRUCTURAL AND THERMAL OPTIMIZATION OF CHARCOAL STOVES FOR IMPROVED EFFICIENCY AND DURABILITY

Isah, M. Z., Abioye, A. M., and Fachway, A. A.

Department of Mechanical/Production Engineering, Abubakar Tafawa Balewa University, Bauchi, Nigeria

Email: amadekunle@atbu.edu.ng

Abstract

*Charcoal stoves are widely used in many regions for cooking; however, traditional designs often suffer from poor thermal efficiency and structural weaknesses. Optimizing the design of these stoves can significantly improve their performance, leading to energy savings and a reduced environmental impact. This study focused on the structural and thermal optimization of charcoal stoves to enhance both efficiency and durability through material selection, structural analysis, and thermal performance improvements. Structural simulations were conducted using SolidWorks to evaluate the integrity of the stove material, and 1 mm of mild steel was identified as a suitable choice for stove construction owing to its strength. Thermal analysis was also performed in SolidWorks to assess the heat distribution and energy retention. Additionally, the Response Surface Methodology (RSM) was used to determine the optimal thickness of the insulation and air gap to minimize heat loss. Experimental evaluations were then conducted to compare the thermal efficiency of an improved stove design against a traditional clay stove using specific metrics, such as burning rate, specific fuel consumption (SFC), and thermal efficiency. The optimal insulation thickness and air gap were determined to be 46.5 mm and 0 mm, respectively, through RSM analysis. Experimental evaluations revealed that the improved stove design achieved a thermal efficiency of 15.06% during the water boiling and rice cooking tests, whereas the traditional clay stove exhibited a lower efficiency of 13.70%. The improved stove had a burning rate of 0.00619 kg/min and a specific fuel consumption (SFC) of 0.4 kg/kg for rice cooking. These results underscore the effectiveness of the optimized design in enhancing the stove performance. The structural and thermal optimization of charcoal stoves significantly improves their efficiency and durability, as demonstrated in this study.***

Keywords: *Stove, Charcoal, Thermal energy, Insulator, Optimization.*

1.0 Introduction

Energy is one of humanity's most essential needs, and significant efforts and technologies have been devoted to providing affordable and sustainable energy. Cooking, a process that takes place both domestically and commercially, demands substantial energy for activities such as boiling, steaming, frying, and meal preparation (Amiebenomo et al., 2023). Approximately 2.9 billion people cannot access secure and affordable clean cooking fuels and technologies. Despite numerous studies and initiatives aimed at creating and deploying more efficient stoves, these efforts often fall short because the stove designs, fuel availability, or management issues fail to align with the users' needs and preferences (Gill-Wiehl et al., 2021). The choice of cooking fuel in a household is influenced by several key factors, including income, location, firewood price, hours of electricity supply, and home ownership. Each of these elements significantly impacts the type of cooking fuel that households adopt (Danlami et al., 2018). Given the current situation in Nigeria, finding any affordable commodity is challenging. The cost of charcoal is high. As a result, there is a pressing need to recommend more energy-efficient stoves, which can reduce the amount of charcoal needed and alleviate some of the financial strain (Tsoho & Tajiri, 2022). In Sub-Saharan Africa, reliance on wood fuel has significantly depleted vegetative resources. Although there are hundreds of improved cooking stoves available, many have not achieved their full potential because their designs mainly emphasize either fuel efficiency or smoke reduction (Bantu et al., 2018). African women are particularly vulnerable to health hazards from smoke-filled environments created through traditional cooking methods. The need to create an eco-friendly and convenient cooking atmosphere has driven research to improve existing stove designs (Tiew et al., 2024; Okorun et al., 2023). Biomass cookstoves have been actively designed for decades, leading to significant advancements in cleaner and more efficient stoves. However, developing high-performance, high-quality products that meet user preferences and remain affordable remains an ongoing challenge. Several factors contribute to this difficulty, including limited financial resources, lack of awareness, and cultural preferences (Sweeney, 2017). For millennia, wood fuel has been a primary source of energy. However, with the increasing human population and the reduction of forest cover, this essential resource is becoming unsustainable. Although improved cookstoves could help address this issue, their adoption rate remains low because people do not perceive their benefits or face barriers in accessing these technologies (Mutuku et al., 2022). Due to the high cost of electricity, liquefied petroleum gas (LPG), and kerosene or paraffin oil, there is a need to develop alternative heating solutions for rural and urban households, restaurants, and other business operations and facilities (Oyejide et al., 2023). Many initiatives aimed at improving cooking stoves have been implemented in Sub-Saharan Africa (SSA). These programs seek to limit indoor air pollution, enhance the quality of life for women, reduce the usage of fuel, particularly charcoal, thereby mitigating deforestation, alleviate the financial burden of energy costs on low-income populations, and improve user health by lowering exposure to environmental toxins. Collectively, these efforts contribute to sustainable development and the well-being of communities in the region (Kaputo et al., 2023). Over the past two decades, numerous developing countries have initiated programs and interventions aimed at enhancing the efficiency of household wood and charcoal stoves. These initiatives have been driven by the need to address energy security, environmental sustainability, and public health issues. Despite the progress made, challenges remain in achieving widespread adoption and sustained use of improved stoves. Factors such as cultural acceptance, affordability, availability of alternative fuels, and support infrastructure play critical roles in the success of these programs (Petro, 2020). Efforts to improve stove efficiency and reduce emissions are crucial not only for environmental preservation but also for improving the health and economic conditions of communities. Innovations in stove design, coupled with effective dissemination and education strategies, are essential to ensure that the benefits of these technologies are realized. Research and development must continue to focus on creating stoves that are user-friendly, cost-effective, and adaptable to local conditions, ensuring that they meet the diverse needs of the populations they are intended to serve.

2.0 Materials and Method

2.1 Material Selection

2.1.1 Mild steel

Table 1 presents the properties of mild steel. Mild steel, known for its versatility and cost-effectiveness, is commonly used in engineering and construction.

Table 1: Properties of Mild Steel

Property	Value	Units
Elastic Modulus	200000	N/mm^2
Poisson's Ratio	0.3	N/A
Shear Modulus	80000	N/mm^2
Mass Density	7870	kg/m^3
Tensile Strength	700	N/mm^2
Compressive Strength	500	N/mm^2
Yield Strength	350	N/mm^2
Thermal Expansion Coefficient	13×10^{-6}	/K
Thermal Conductivity	51.9	W/(m·K)
Specific Heat	472	J/(kg·K)

The properties listed include the elastic modulus, Poisson's ratio, shear modulus, mass density, tensile strength, compressive strength, yield strength, thermal expansion coefficient, thermal conductivity, and specific heat. These characteristics were critical for determining the performance and suitability of mild steel used in this study.

2.1.2 Glass wool

Table 2 presents the physical properties of Glass wool used in this study. This material was selected for its excellent thermal insulation, low weight, and widespread availability.

Table 2: Properties of Glass Wool

Property	Value	Units
Elastic Modulus	2000	N/mm^2
Poisson's Ratio	0.394	N/A
Shear Modulus	318.9	N/mm^2
Mass Density	200	kg/m^3
Tensile Strength	0.02	N/mm^2
Thermal Expansion Coefficient	4.8×10^{-6}	K^{-1}
Thermal Conductivity	0.0399999	W/(m·K)
Specific Heat	670	J/(kg·K)

The presented properties—elastic modulus, Poisson's ratio, shear modulus, density, tensile strength, thermal conductivity, and specific heat—are crucial for assessing Glass wool's suitability as an insulation material in this study.

2.2 Methods

2.2.1 Modelling and simulation

The present study employed the SolidWorks software as the principal modelling tool to develop a comprehensive and precise model. Additionally, the advanced features of the SolidWorks static and thermal simulations were utilized. This methodological approach ensures an accurate representation of the model, thus enabling a precise analysis and evaluation within an academic framework.

2.2.1.1 Static analysis

SolidWorks Simulation employs principles of equilibrium, material behaviour, and compatibility to conduct static structural analysis. The governing equations, which include equilibrium equations $\left(\sum F_x = 0, \sum F_y = 0, \sum M = 0\right)$, Constitutive Equations (Hooke's Law for linear elastic materials), $(\sigma = E.\epsilon)$ and compatibility equations.

$$\left(\frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 v}{\partial x\,\partial y} + \frac{\partial^2 w}{\partial x^2} = 0\right) \quad \text{... (1)}$$

are applied to each finite element using the Finite Element Method (FEM). This numerical approach enables the analysis of displacements, strains, stresses, and factors of safety, allowing engineers to validate simulation results, ensure design reliability, and advance safe and efficient engineering practices.

2.2.1.2 Thermal analysis

In SolidWorks Simulation, thermal analysis encompasses the principles of heat transfer through conduction, convection, and radiation governed by a set of fundamental equations. The transient heat conduction in a solid body is described by the equation

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(K\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(K\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(K\frac{\partial T}{\partial z}\right) + \dot{q}_{gen} \quad \text{... (2)}$$

where ρ is the materials density, $C_p$is the specific heat capacity, T is temperature, t is time, K is thermal conductivity, and $\dot{q}_{gen}$ represents the heat generation per unit volume. The boundary conditions for convection and radiation were incorporated using Newton's law of cooling and the Stefan-Boltzmann law, respectively. This approach allows the material properties and boundary conditions be accurately defined, enabling the simulation of complex thermal behaviours in various geometries.

2.2.1.3 Optimization

The optimization method in SolidWorks Simulation involves defining an objective function (e.g., minimizing stress or maximizing heat dissipation) and selecting design variables such as geometry dimensions and material properties. Constraints are specified, and a sensitivity analysis is conducted to understand the impact of design variable changes on the objective function. A gradient-based optimization algorithm iteratively adjusts the design variables based on this analysis. Response surface approximations are used to enhance efficiency by predicting the objective function's behaviour. The process continues until convergence criteria are met, ensuring the objective is optimized. The final design is validated through additional simulations or physical testing to confirm practical applicability.

2.3 Performance Evaluation

2.3.1 Moisture Content Determination

Charcoal moisture content was determined through oven-drying. Samples were initially weighed, then dried in an oven at 105°C for two hours. After cooling in a desiccator containing silica gel, samples were reweighed. Moisture content was calculated as the percentage weight loss due to drying.

$$Moisture\ Content(\%) = \frac{Weight\ of\ Charcoal\ with\ moisture\ (g) - weight\ of\ dried\ Charcoal(g)}{Wieght\ of\ charcoal\ with\ moisture(g)} \quad \ldots (3)$$

2.3.2 Determination of the ash content in charcoal

The ash content of the charcoal was determined using Equation 4.

$$Ash\ Content(\%) = \frac{weight\ of\ Ash(g)}{weight\ of\ dried\ charcoal} x100 \quad \ldots (4)$$

2.3.3 Burning rate of the charcoal

The charcoal combustion rate is a critical parameter influencing stove performance. equation 5 was used to quantify this rate.

$$Burning\ rate = \frac{Fuel\ used\ (Kg)}{time\ used\ to\ prepare\ meal(mins)} \quad \ldots (5)$$

2.3.4 Heat transfer through the stove body

Heat transfer through the cylindrical stove body was modelled using Fourier's law for conduction in a hollow cylinder. This law quantifies the heat transfer rate (Q) as a function of the temperature difference (T_1 - T_2) between the inner and outer surfaces, the material's thermal conductivity (k), and the cylinder's geometric properties (length L, outer radius ro, and inner radius ri).

$$Q = \frac{2\pi KL(T_1 - T_2)}{\ln\left(\frac{r_0}{r_i}\right)} \quad \ldots (6)$$

Where: Q = heat transfer rate (W), k =conductivity of the stove material (W/mK), L = length of the cylinder (m) , T_1 = temperature at the inner surface (K) , T_2 = temperature at the outer surface (K), r_o = outer radius of the cylinder (m) and r_i = inner radius of the cylinder (m)

2.3.5 Specific fuel consumption

Specific fuel consumption (SFC) was calculated using Equation 7 to assess the stove's fuel efficiency in terms of fuel consumed per unit of thermal energy output.

$$\text{Specific fuel consumption (SFC)} = \frac{Mass\ of\ consumed\ fuel}{Total\ mass\ of\ cooked\ food} \quad \ldots (7)$$

(Moro, 2020).

2.3.6 Time spent in cooking

The time required to prepare one kilogram of food was calculated using Equation 8 to assess the stove's efficiency in terms of cooking time per unit mass of food.

$$Time\ spent = \frac{Total\ time\ spent\ in\ cooking}{Total\ mass\ of\ cooked\ food} \quad \ldots (8)$$

2.3.7 Water Boiling Test (WBT)

Water Boiling Tests (WBTs) were conducted to assess the stove's performance. This standardized method involves measuring the fuel consumed and time taken to boil a specific volume of water. WBTs provide a practical approach to comparing stove efficiency under controlled conditions. The data obtained from these tests were utilized to calculate thermal efficiency.

2.3.8 Thermal efficiency

The thermal efficiency of the charcoal stove was determined through a water boiling test. This method involves calculating the ratio of the heat absorbed by the water to the heat content of the consumed fuel. The thermal efficiency is given by equation 9

$$\eta_{th} = \frac{M_{wi}C(T_2-T_1)+\left(M_{wi}-M_{wf}\right)L}{M_c\, x\, C_v} \quad \text{... (9)}$$

(Amiebenomo, 2023)

where: M_{wi} = initial mass of water (kg); M_{wf} = final mass of water (kg), T_2 = final temperature of water,^{0}C; T_1 = initial temperature of water(^{0}C), C = specific heat capacity of water(kJkg^{-1}K^{-1}) and L = latent heat of vaporization of water at 100°C (kJkg^{-1}), duration of the test, $M_c = mass\ of\ the\ charcoal$ used and C_v= Calorific value of the charcoal.

3 Result and Discussion

3.1 Design and Bill of Material

3.1.1 Design

The stove was designed to accommodate a standard cooking pot with precise dimensions of 265 mm in diameter and 138 mm in height. The cooking pot has a volume of approximately 7.6 litres.

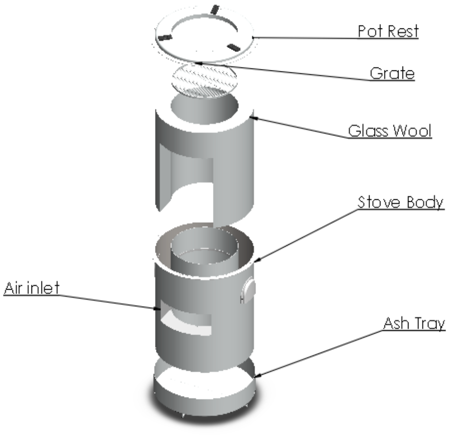

Figure 1: Exploded View

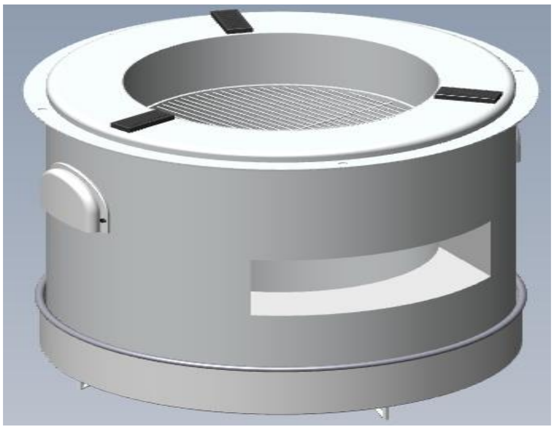

Figure 2: Assembled Stove

Figures 1 and 2 visually represent the charcoal stove design. Figure 1 provides an exploded view, displaying the individual components and their layout, while Figure 2 presents the stove in its fully assembled form, showing how the parts fit together to create the final structure.

3.2. Simulation

3.2.1 Mesh

Figure 3 represents finite element mesh. In this study, a high-quality solid mesh was generated using a blended curvature-based mesher, resulting in 1,109,775 nodes and 577,849 elements with sizes ranging from 0.6 mm to 3 mm. The mesh was predominantly well-shaped, with 96.2% of the elements having an aspect ratio below 3 and only 0.0185% exceeding an aspect ratio of 10, ensuring stability and accuracy.

Figure 3: Finite Element Mesh

Importantly, no distorted elements were identified, indicating a reliable mesh configuration. The meshing process was executed efficiently, completing in less than 10 minutes, without necessitating independent remeshing of any component. This high-quality mesh is well-suited for providing dependable FEA results.

3.2.2 Static analysis

The Table 3 was employed to evaluate the structural integrity of the charcoal stove through a simulation. It outlines the mass of the pot, the mass of the pot when filled with water, and the corresponding weight of the pot with water under various conditions. These data were essential for simulating real-world loading scenarios encountered by charcoal stoves. By analysing the stove's response to different loads, the simulation provided an understanding of the stress distribution, strain, and displacement, ensuring that the stove could maintain its structural integrity and perform safely and reliably under typical operating conditions.

Table 3: Data used in the static analysis

S/N	Mass of Pot	Mass of pot with water	Weight of pot with water
1	0.45	3.10	31.0
2	0.55	4.65	46.5
3	0.75	5.85	58.5
4	0.8	7.10	71.0
5	0.90	8.51	85.1

Figures 4–6 provide a detailed analysis of the material's mechanical response to a 31-Newton load, showcasing stress, strain, and displacement, respectively. In contrast, Figures 7, 8, and 9 present the equivalent data for a substantially higher load of 85.1 Newtons. This comparative representation allows for a comprehensive understanding of the behavior of a material across a range of loading conditions.

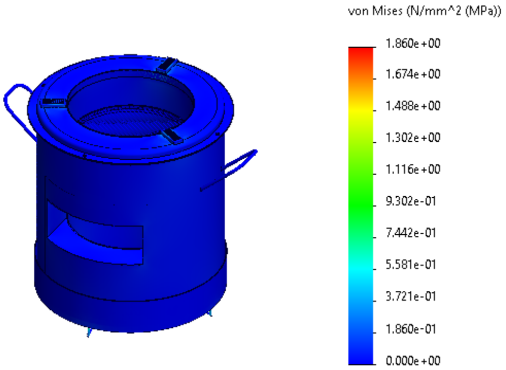

Figure 4: Stress plot for 31N weight applied.

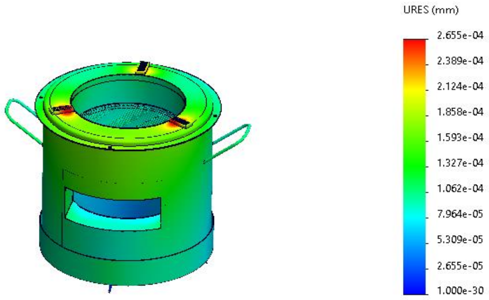

Figure 5: Displacement plot for 31N weight applied.

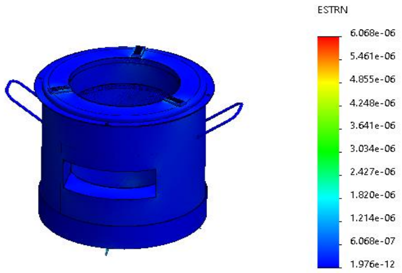

Figure 6: Strain plot for 31N weight applied.

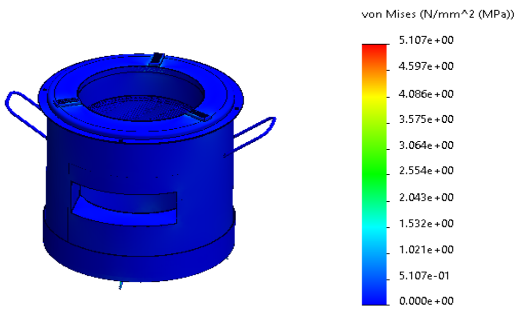

Figure 7: Stress plot for 85.1N weight applied.

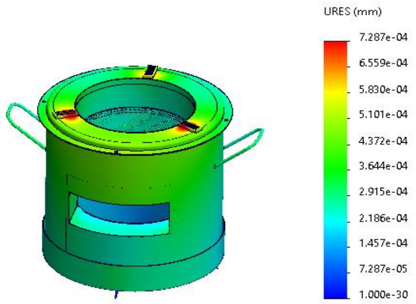

Figure 8: Displacement plot for 85.1N weight applied.

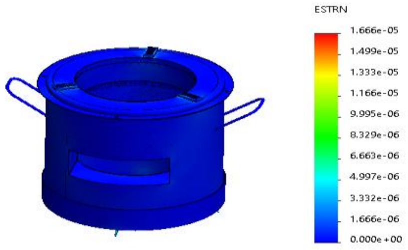

Figure 9: Strain plot for 85.1N weight applied.

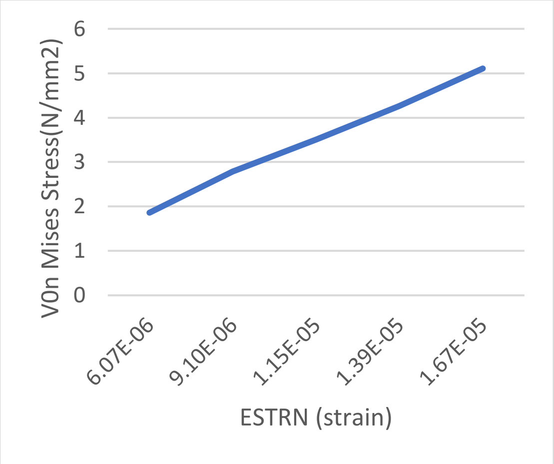

Figure 10: Stress-Strain Curve

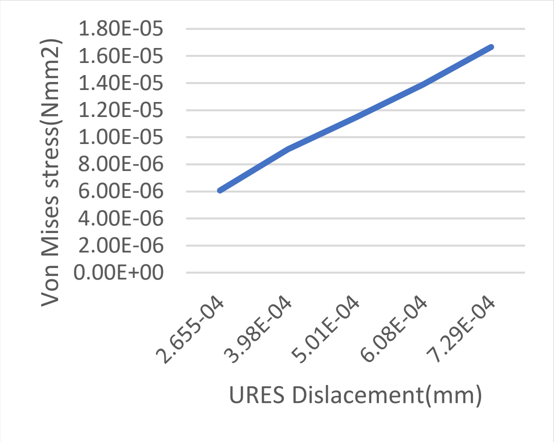

Figure 11: Stress- Displacement Curve

Figure 10 illustrates the relationship between stress and strain, showing a nearly linear correlation, indicating that the material exhibited elastic behaviour within the tested range, consistent with Hooke's law. The increase in stress resulted in a proportional increase in strain, suggesting that the material remained within its elastic region. Figure 11 depicts the relationship between stress and displacement, demonstrating a linear trend, where the displacement increased predictably with the application of stress. This behaviour implies that the material deformed consistently under load, with no signs of yielding or failure within the observed stress levels. The findings confirmed that the material can withstand applied stress while maintaining its structural integrity.

3.2.3 Thermal Analysis

Thermal simulation is a crucial method for understanding and improving stove performance. It allows for the analysis of heat transfer processes, revealing aspects such as combustion efficiency, heat distribution, and overall thermal performance. The combustion temperature range of charcoal, as reported by Lubwama et al., 2021, is 741.6-785.9 °C. To investigate the stove's behavior under conditions both within and outside this range, the present study considered temperatures of 500 °C (below the reported range) and 1000 °C (above the reported range).

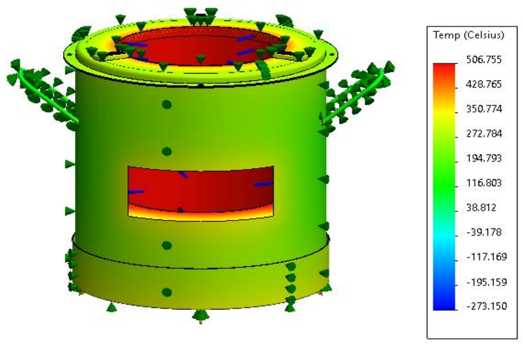

Figure 12: Temperature Distribution at 500°C

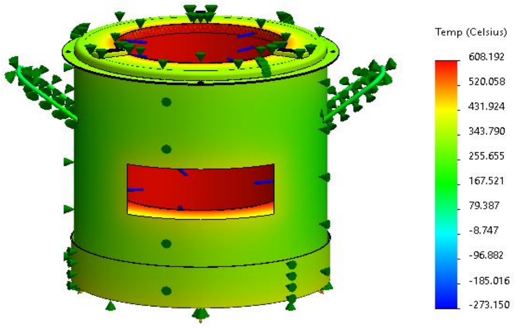

Figure 13: Temperature Distribution at 600°C

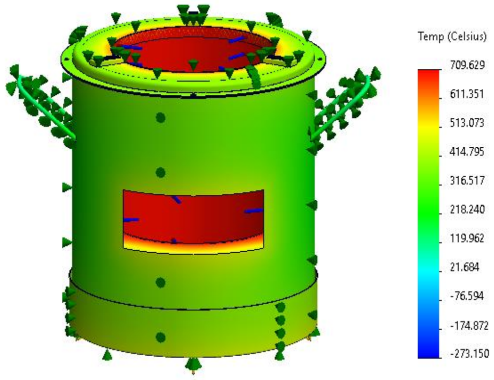

Figure 14: Temperature Distribution at 700°C

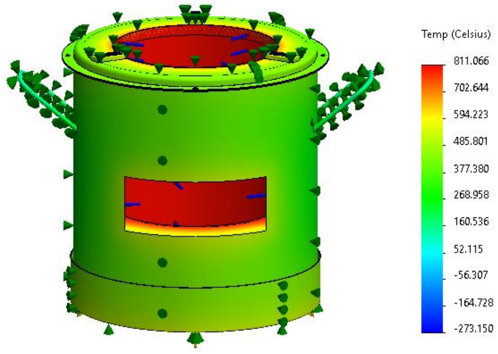

Figure 15: Temperature Distribution at 800°C

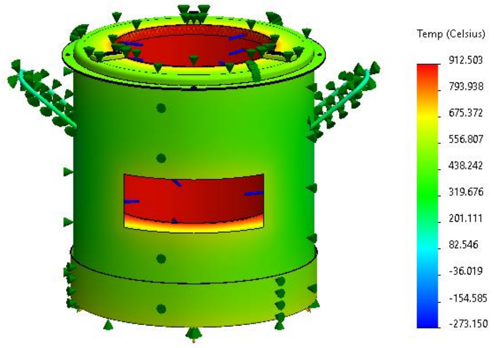

Figure 16: Temperature Distribution at 900°C

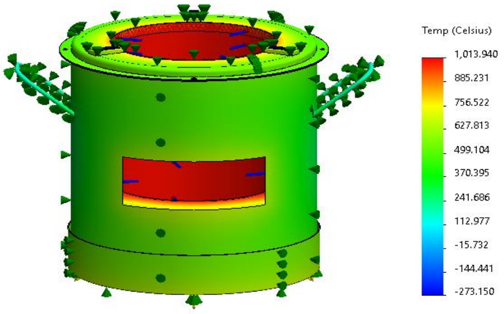

Figure 17: Temperature Distribution at 1000°C

Thermal simulations were performed to evaluate temperature distribution on the stove's surface. Figure 12 depicted the outer surface temperature at a lower combustion temperature, showing a significant reduction due to the insulating effect of the glass wool. Figure 17 illustrated the temperature distribution at a higher combustion temperature, where the insulation continued to effectively moderate the outer surface temperature. The series of figures from 12 to 17 shows the impact of both combustion temperature and insulation, demonstrating how glass wool effectively manages heat transfer and contributes to the stove's thermal performance.

3.2.4 Optimisation

Table 4 represents the design of the experiment data, the design of Experiment (DOE) was conducted to systematically evaluate the influence of air gap and insulation thickness on wall temperature. Subsequent Response Surface

Methodology (RSM) analysis revealed a quadratic relationship between these variables and the response, suggesting a complex interaction between the factors. While the model predicted an optimal combination of 1mm air gap and 45.5 mm insulation thickness, experimental validation confirmed this as the condition yielding the lowest wall temperature.

Table 4: Central Composite Design of Experiment

Air Gap (mm)	Insulation Thickness (mm)	wall Temperature (°C)	StdOrder	RunOrder	Blocks	PtType	FITS1
36	10.5	56.9	1	1	1	1	55.9649
31	15.5	50.4	2	2	1	1	51.9693
26	20.5	48.9	3	3	1	1	48.3792
21	25.5	45.2	4	4	1	1	45.1946
16	30.5	42.0	5	5	1	1	42.4156
11	35.5	40.1	6	6	1	1	40.0422
6	40.5	39.2	7	7	1	1	38.0743
1	45.5	37.1	8	8	1	1	36.5119
0	46.5	35.0	9	9	1	1	36.2481

The data presented in Figure 1 shows a clear trend of decreasing air gap and increasing insulation thickness significantly reducing wall temperature. Starting with an air gap of 36 mm and insulation thickness of 10.5 mm, the wall temperature is relatively high at 56.9°C. As the air gap decreases and insulation thickness increases, the wall temperature steadily drops, reaching a minimum of 35.0°C at 0 mm air gap and 46.5 mm insulation thickness.

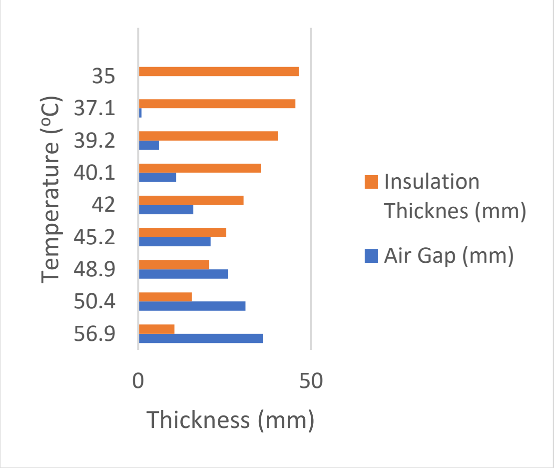

Figure 18: Effect of Insulation and air gap thickness on the outer surface temperature of the stove.

This non-linear decrease in temperature suggests a complex interaction between the two variables, with their optimal combination resulting in the lowest wall temperature, as predicted and validated by the Response Surface Methodology (RSM) analysis.

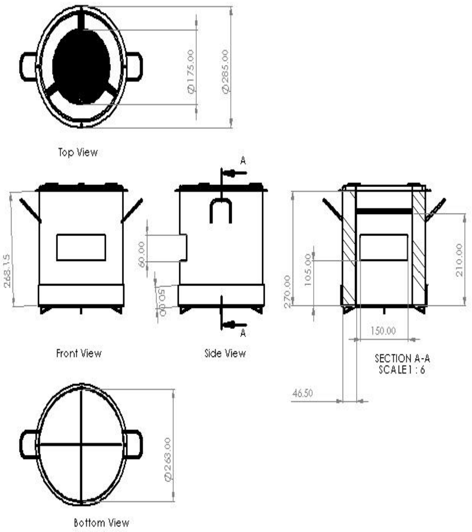

Figure 19: Detailed assembly drawing

Figure 19 presents an assembly drawing of the improve charcoal stove. This drawing illustrates the stove's components and their spatial arrangement, including essential dimensions for accurate construction.

3.3 Bill of Engineering Materials for the Stove

The engineering design and fabrication of a device involve more than the simple assembly of materials; it is a complex process that requires careful consideration of numerous factors, including cost optimization. The Bill of Engineering Measurement and Evaluation (BEME) specifically addresses the financial aspects associated with the design and fabrication of a charcoal stove. Table 5 provides an assessment of expenses related to labour, procurement, and other financial considerations, ensuring that all costs associated with the project are thoroughly accounted for.

Table 5: List of Bill of Materials

SN	Item	Quanty	Unit Price	Cost (N)
1	Sheet of mild steel	¼	8000	8000
2	quarter rod	2	1000	2000
3	Paint	1	2000	2000
4	Glass wool	1	1500	1500
5	Labour	1	3000	3000
			Total	16500

Figures 19 to 22 provide various perspectives of the constructed stove.

Figure 20: Side View

Figure 21: front View

Figure 22: Top View

Figure 23: Bottom View

3.4 Performance Evaluation

3.4.1 Moisture content determination

$$Moisture\ Content(\%) = \frac{Weight\ of\ Charcoal\ with\ moisture\ (g) - weight\ of\ dried\ Charcoal(g)}{Wieght\ of\ charcoal\ with\ moisture(g)}$$

$$= \frac{2.0-1.95}{1.95} \text{ x } 100$$

$$= 2.6\%$$

3.4.2 Determination of the ash content in charcoal

The ash content of the charcoal was determined using Equation 4.

$$Ash\ Content(\%) = \frac{weight\ of\ Ash(g)}{weight\ of\ dried\ charcoal} x100$$

$$= \frac{0.002}{1.95} x100 = 0.102\%$$

3.4.3 Water boiling rest

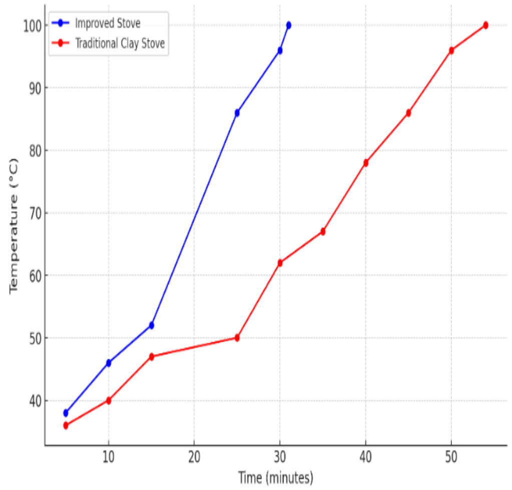

Figure 24: Temperature plot against time

Figure 24 presents a comparative analysis of the temperature against time for an improved stove and a traditional clay stove, revealing a pronounced disparity in heating efficiency. The former exhibited a rapid temperature increase, achieving a boiling point within 31 min, indicating superior heat transfer and energy conversion. In contrast, the latter demonstrated a gradual temperature increase, indicating less efficient heat utilization.

3.4.4 Improved stove

3.4.4.1 Burning rate of the charcoal

$$Burning\ rate = \frac{Fuel\ used\ (Kg)}{time\ used\ to\ prepare\ meal(mins)} = \frac{0.26}{42min}$$

$$= 0.00619\text{kg/min}$$

3.4.4.2 Specific fuel consumption

Specific fuel consumption (SFC)

$$= \frac{Mass\ of\ consumed\ fuel}{Total\ mass\ of\ cooked\ food} = \frac{0.26kg}{0.65}$$

$$\approx 0.40\text{kg/kg}$$

3.4.4.3 Time spent in cooking

$$Time\ spent = \frac{Total\ time\ spent\ in\ cooking}{Total\ mass\ of\ cooked\ food}$$

$$= \frac{42}{0.65} = 64.6\text{mins/kg}$$

3.4.4.4 Thermal efficiency

$$\eta_{th} = \frac{M_{wi}C(T_2 - T_1) + (M_{wi} - M_{wf})L}{M_c\ x\ C_v}$$

$$= \frac{2.7\ x\ 4.182\ x\ (100-28) + (2.7-2.55)\ x\ 2260}{0.2\ \ x\ 38240}$$

$$= \frac{1{,}152{,}369.6}{7648000}\ \text{X}\ 100 = 15.06\%$$

3.4.5 Stove made of Clay

3.4.5.1 Burning rate of the charcoal

$$Burning\ rate = \frac{Fuel\ used\ (Kg)}{time\ used\ to\ prepare\ meal(mins)} = \frac{0.2}{60min}$$

$$= 0.00333\text{kg/min}$$

3.4.5.2 Specific Fuel Consumption

Specific fuel consumption (SFC)

$$= \frac{Mass\ of\ consumed\ fuel}{Total\ mass\ of\ cooked\ food}$$

$$= \frac{0.2kg}{0.65} \approx 0.31\text{kg/kg}$$

3.4.5.3 Time spent in cooking

$$Time\ spent = \frac{Total\ time\ spent\ in\ cooking}{Total\ mass\ of\ cooked\ food} = \frac{60}{0.65}$$

$$\approx 92.3\text{mins/kg}$$

3.4.5.4 Thermal efficiency

$$\eta_{th} = \frac{M_{wi}C(T_2 - T_1) + (M_{wi} - M_{wf})L}{M_c\ x\ C_v}$$

$$= \frac{2.7\ x\ 4.182\ x\ (100-28) + (2.7-2.55)\ x\ 2260}{0.22\ \ x\ 38240}$$

$$= \frac{1{,}152{,}369.6}{8412800}\ \text{X}\ 100 = 15.06\% \approx 13.70\%$$

3.5 Conclusion

This research aimed to enhance the structural and thermal efficiency of charcoal stoves, particularly for both commercial and domestic cooking applications. By modifying existing stove designs and employing advanced modelling and simulation techniques using SolidWorks, this study successfully developed an optimized charcoal stove that addresses key inefficiencies observed in traditional designs. The stove was constructed using 1 mm mild steel, which was determined to have the necessary structural integrity to withstand regular use. The design of the stove incorporated features such as optimized insulation thickness (46.5 mm) and the elimination of air gaps, which were identified through Response Surface Methodology (RSM) as the most effective configuration for minimizing heat loss and enhancing thermal performance. Experimental tests showed that the improved stove achieved a thermal efficiency of 15.06%, surpassing the 13.70% efficiency of traditional clay stoves. The burning rate of the stove was recorded at 0.00619 kg/min, and the specific fuel consumption (SFC) was 0.4 kg/kg for rice cooking, indicating substantial improvements in fuel efficiency. These enhancements not only contribute to more effective cooking but also reduce overall fuel consumption, offering both environmental and economic benefits.

Reference

Adamu, M. B., Adamu, H., Ade, S. M., & Akeh, G. I. (2020). Household energy consumption in Nigeria: A review on the applicability of the energy ladder model. *Journal of applied sciences and environmental management*, *24*(2), 237-244.

Agyemang, A., Tawiah, P. O., & Nyarko, F. (2014). Efficient charcoal stoves: Enhancing their benefits to a developing country using an improved design approach. *International Journal of Engineering Trends and Technology*, 15(2), 94-98

Amiebenomo, S. O., Udeji, F. O., & Aigbokie, J. I. (2023). Design and fabrication of an industrial charcoal cooker. *International Journal of Science, Engineering and Technology*, 11(5).

Bantu, A. A., Nuwagaba, G., Kizza, S., & Turinayo, Y. K. (2018). Design of an improved cooking stove using high density heated rocks and heat retaining techniques. *Journal of Renewable Energy*, *2018*(1), 9620103.

Danlami, A. H., Applanaidu, S. D., & Islam, R. (2018). An analysis of household cooking fuel choice: a case of Bauchi State, Nigeria. *International Journal of Energy Sector Management*, *12*(2), 265-283.

Gill-Wiehl, A., Price, T., & Kammen, D. M. (2021). What’s in a stove? A review of the user preferences in improved stove designs. *Energy Research & Social Science*, *81*, 102281.

Kamara, S. Design and Production of an Improved Cook Stove with Swinging Combustion Chamber to Enable Refueling for Continuous Operation. In BOOK OF PROCEEDINGS (p. 170).

Kaputo, K., Mwanza, M., & Talai, S. (2023). A review of improved cooker stove utilization levels, challenges and benefits in sub-Saharan Africa. *Journal of Energy Research and Reviews*, *14*(1), 9-25.

Lubwama, M., Yiga, V. A., Ssempijja, I., & Lubwama, H. N. (2021). Thermal and mechanical characteristics of local firewood species and resulting charcoal produced by slow pyrolysis. *Biomass Conversion and Biorefinery*, 1-16.

Mekonnen, B. A. (2020). Design and Performance Evaluation of Rocket Stove for Cleaner Cooking in Rural Ethiopia.

Moro, A., Baffoe, B. F., Dalaba, M., & Oduro, A. (2020). Fuel Consumption for Various Dishes for a Wood-Fueled and Charcoal Fueled Improved Stoves used in Rural Northern Ghana. *International Journal of Environmental Sciences and Natural Resources*, *25*(1), 042-053.

Musonda, K. E., & Mutembo, S. (2024). Adjustable Sawdust Stove for Optimal Pot Placement and Improved Insulation Materials. *Journal of Renewable Energy*, *2024*(1), 6525754.

Mutuku, K., Njoka, F., & Hawi, M. (2022). Design, development and evaluation of a modifie d improved charcoal cookstove for space heat and power generation. *Int. J. Eng. Res. Technol*, *15*, 119-129.

Ochieng, C. A., Zhang, Y., Nyabwa, J. K., Otieno, D. I., & Spillane, C. (2020). Household perspectives on cookstove and fuel stacking: A qualitative study in urban and rural Kenya. *Energy for Sustainable Development*, *59*, 151-159.

Okorun, A. A., Agbadua, S. A., Adeniji, A. O., Dickson, M. A., & Agina, E. C. (2023). Design and optimization of charcoal economy energy efficient stove. *International Research Journal of Modernization in Engineering Technology and Science, 5*(3), 4118-4127

Otieno, A. O., Home, P. G., Raude, J. M., Murunga, S. I., & Gachanja, A. (2022). Heating and emission characteristics from combustion of charcoal and co-combustion of charcoal with faecal char-sawdust char briquettes in a ceramic cook stove. *Heliyon*, *8*(8).

Owusu-Amankwah, G., Abubakari, S. W., Apraku, E. A., Iddrisu, S., Kar, A., Malagutti, F., ... & Jack, D. (2023). Socioeconomic determinants of household stove use and stove stacking patterns in Ghana. *Energy for Sustainable Development*, *76*, 101256.

Oyejide, O. J., Okwu, M. O., & Tartibu, L. K. (2023). Adaptive design and development of a modular water hyacinth briquette stove. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(3), 6515-6533.

Petro, L. (2020). *Optimization of domestic biogas stove burner for efficient energy utilization* (Doctoral dissertation, NM-AIST).

RS, B., MA, O., & TA, A. (2015). Design and performance evaluation of supplemental air supplied charcoal stove. *International Letters of Chemistry, Physics and Astronomy*, *54*, 1-10.

Sweeney, D. (2017). Handbook for biomass cookstove research, design and development, A practical guide to implementing recent advances. *Global Alliance for Clean Cookstove and the MIT D-Lab*.

Tiew, S. C., Abakar, Y. A., Mohammed, I. Y., Abubakar, L. G., Bawa, M. A., Obiajunwa, o., Liman, H, & Abubakar, N. A. (2024). Modelling and Fluid Dynamics of Combustion Process and Energy Efficiency of a Digital Stove for Domestic Application. *Nigerian Journal of Tropical Engineering*, 18(2), 244-252.

Tsoho, A., & Tajiri, S. B. (2022). Comparative Study on Efficiency of some Common Charcoal Stoves for Domestic Application in Sokoto Metropolis. *International Journal of Advances in Engineering and Management,* 4(10), 920-92.