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Development and Performance Evaluation of a Dual-Purpose Biomass Cookstove for Cooking and Grilling Applications

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Abstract: The persistent dependence on traditional biomass cookstoves in developing countries continues to pose significant challenges related to household air pollution, inefficient fuel utilisation, and environmental degradation. This study presents the design, fabrication, and performance evaluation of a dual-purpose biomass cookstove capable of both cooking and grilling, fueled by wood and charcoal. The stove was designed with an improved combustion chamber, controlled air supply, and a chimney system to enhance thermal efficiency and reduce emissions. A numerical transient thermal analysis was carried out using ANSYS to investigate the temperature distribution and heat flux within the stove body under time-dependent operating conditions. Experimental performance evaluation was conducted through water-boiling and grilling tests, and the results were benchmarked against data from conventional and moderately efficient stoves reported in the literature. The fabricated stove demonstrated progressive temperature rise, stable heat flux distribution, and acceptable cooking and grilling performance, with reduced smoke release due to effective venting of combustion products. Although the boiling and grilling times were slightly longer than those on open fire and average grill stoves, the dual-purpose stove offered improved safety, versatility, and emission control. The findings confirm the technical feasibility of a low-cost, locally fabricated dual-purpose biomass cookstove suitable for domestic use, particularly in rural and peri-urban settings.

Keywords: Biomass Cookstove; Dual Purpose Stove; Thermal Analysis; Water Boiling Test; Grilling Performance; Household Energy; Fuel Utilisation; Performance Evaluation; Cooking and Grilling.

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1. Introduction

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One of the biggest problems in many low- and middle-income countries is still access to clean, reliable, and affordable energy for the home. A large number of households, especially in rural and peri-urban areas, rely almost entirely on traditional biomass fuels such as firewood, charcoal, agricultural waste, and animal dung for cooking and preparing food every day. People often choose these fuels because they are easy to find, they know how to use them, and they don't cost much. But when used in traditional stoves and open-fire systems, they burn inefficiently, consume excessive fuel, and emit significant amounts of harmful pollutants. In poorly ventilated indoor spaces, these emissions build up quickly, putting people in the home at risk of dangerous levels of carbon monoxide, particulate matter, and other harmful chemicals. Many studies have found that burning biomass in the home can cause respiratory infections, chronic obstructive pulmonary disease, heart problems, eye problems, and poor pregnancy outcomes. This makes it one of the most serious environmental health risks worldwide [1]; [2]. More than 2.7 billion people worldwide still use inefficient biomass-based cooking technologies. Most of these people live in sub-Saharan Africa and parts of South and Southeast Asia [3]. In these areas, households are forced to continue using traditional fuels because they lack easy access to modern energy sources such as electricity, liquefied petroleum gas, or natural gas. Nigeria is a particularly important example because many households use biomass fuels, especially in rural areas where energy poverty remains common. Many households find it hard to switch to modern fuels due to high initial costs of clean cooking technologies, unreliable electricity supply, poor distribution infrastructure, and changing fuel prices [4]. So, even when cleaner options are available, they are often too expensive or too hard to reach, making people even more reliant on traditional biomass systems. Universal access to clean, modern energy remains a key part of global development plans, but the truth is, it will take time to move away from biomass.

In this situation, better biomass technologies have become a practical and realistic way to make the transition. Improved biomass cookstoves are designed to address the biggest problems with traditional stoves by burning more efficiently, using less fuel, and emitting less pollution. They still use fuels that are easy to find and culturally acceptable. Studies have demonstrated that design enhancements, including optimised combustion chambers, improved insulation, regulated airflow, and the incorporation of chimneys or hoods, can markedly reduce indoor air pollution and enhance thermal efficiency [5]. These changes not only make people healthier but also reduce the amount of fuel needed for daily cooking. This means less time and work spent gathering fuel, which mostly affects women and children. Even with these improvements, many new cookstove designs focus only on cooking tasks like boiling, frying, or simmering and don't account for other common ways to prepare food. In many places, people regularly grill and roast food on separate devices or over open fires. This uses more fuel and releases more pollutants into the air. Using multiple cooking and grilling systems also increases energy use and places greater strain on users, both physically and financially [6]; [7]. Grilling over an open fire is often associated with inefficient fuel use and exposure to significant smoke, since it usually occurs outdoors or in semi-enclosed spaces where emissions aren't well controlled [8]. These practices show that there is a significant problem with current improved cookstove solutions: they lack multifunctional designs that can meet different cooking needs within a single system. To fill this gap, stove design needs to be more comprehensive and based on how people really use energy in their homes. The creation of a biomass cookstove that can both cook and grill in one unit is a big step in the right direction. By combining these functions, this type of cooker could use energy more efficiently, reduce the number of devices needed, and make cooking easier every day.

Combining cooking and grilling functions can also help you use heat more efficiently. This is because you can better control and direct the energy generated during combustion based on what you are doing. This integration is especially useful in places where space is tight, and families want small, versatile appliances that fit with how people cook in the area. When designing and building a biomass cookstove that can do more than one thing, you need to carefully consider how well it performs in terms of heat, which materials to use, how safe it is for users, and how easy it is to use. Using materials that are easy to find in the area is very important to keep costs down, make things easier to make, and enable local repair. You can make strong, inexpensive stove structures by combining materials like mild steel, clay, refractory bricks, and insulation you can find nearby. Numerical thermal analysis is also very important for understanding how heat moves through the cooker. It helps designers improve the combustion chamber shape, airflow, and heat distribution for both cooking and grilling. Before building physical prototypes, computational modelling can help determine temperature profiles, identify heat-loss points, and assess how design changes will affect the final product. It is just as important to test the cooker in real-world conditions to make sure it works as intended. You can use standardised testing protocols to measure key performance indicators such as thermal efficiency, specific fuel consumption, cooking time, grilling effectiveness, and emission levels. User-centred testing, which means watching and getting feedback from potential users, gives you useful information about usability, cultural acceptance, and practical problems that you might not see from lab tests alone. This type of testing ensures that the cooker not only works well technically but also meets the needs and wants of the target community, which is important for getting many people to use it.

The development of a dual-purpose biomass cookstove has broader implications beyond a single household. Better energy efficiency and less fuel use can help ease the strain on local biomass resources at the community level. This can help protect forests and reduce environmental damage. Reduced pollution also means better air quality, which benefits everyone, not just people who use stoves. From a policy perspective, multifunctional biomass stoves align with national and international efforts to make energy use more sustainable, reduce greenhouse gas emissions, and improve public health. They can be a short-term fix that complements longer-term investments in clean energy infrastructure, especially in areas where switching to modern fuels isn't yet feasible. Also, improving cookstoves in the community can boost the local economy and help people learn new skills. Networks for small-scale production and distribution can create jobs and help people in the area own their own energy solutions. When combined with awareness campaigns and supportive policies, these programs can accelerate the adoption of better cooking technologies and maximise their social and environmental benefits. The fact that this cooker can cook and grill simultaneously makes it even more appealing to users and increases the likelihood that they will keep using it over time. In short, many developing countries still depend on traditional biomass fuels for household energy, which harms health, the environment, and the economy. The ultimate goal is to switch to clean and modern energy sources. Still, better biomass cookstoves are a practical and immediate way to lessen the negative effects of traditional cooking methods. The creation of a dual-purpose biomass cookstove that can be used for both cooking and grilling fills a major gap in current technologies by making stoves more useful for real-life household needs. Through careful planning, numerical thermal analysis, and experimental validation, these systems demonstrate that multifunctional biomass stoves could be a long-lasting, culturally appropriate way for households to obtain energy. The results provide significant insights into the ongoing endeavour to enhance energy accessibility, elevate public health, and foster environmental sustainability in resource-limited contexts [8].

2. Literature Review

2.1. Global Use and Impacts of Biomass Cookstoves

Biomass cookstoves remain the dominant cooking technology for billions of people worldwide, particularly in low-income regions [9]; [11]. Their continued use is driven by fuel availability, low upfront cost, and cultural familiarity. However, traditional stoves are highly inefficient, often converting less than 15% of the fuel's chemical energy into useful heat [12]. The remaining energy is lost through incomplete combustion and heat dissipation to the surroundings. The health impacts associated with traditional biomass stoves are well documented [10]. Prolonged exposure to smoke from biomass combustion has been linked to respiratory infections, chronic obstructive pulmonary disease, cardiovascular problems, and adverse pregnancy outcomes [13]; [14]. Women and young children are especially vulnerable due to their proximity to cooking areas. In addition to health concerns, biomass stove emissions contribute to environmental problems such as deforestation, black carbon deposition, and greenhouse gas emissions [15]-[17]. Efforts to address these challenges have focused on disseminating improved cookstoves that offer higher efficiency and lower emissions. Studies have shown that even modest design improvements can result in meaningful reductions in fuel consumption and indoor air pollution [18]; [19]. Nevertheless, adoption rates remain inconsistent, highlighting the need for designs that align with user needs, cooking practices, and economic realities.

2.2. Evolution and Design Principles of Cookstoves and Grill Stoves

The evolution of cookstoves reflects humanity's attempts to improve safety, efficiency, and convenience in food preparation. Early open-fire systems gradually gave way to enclosed stoves with chimneys, improved heat retention, and better airflow control (Figure 1).

Figure 1: (a) Three-stone open fire, (b and c) Metallic open fire, (d) Traditional charcoal stove, (e) Natural-draft double burner biomass cookstove, (f) Husk biomass cookstove, (g) Inverted downdraft gasifier cookstove, (h) Improved biomass cookstove [22]

The introduction of metal stoves during the industrial era further enhanced durability and heat transfer characteristics. Grill stoves followed a similar evolutionary path, transitioning from open-fire grilling to more controlled systems fueled by charcoal, gas, or electricity. While open grills provide high heat transfer rates, they are associated with significant energy losses and high emissions. Modern grill designs emphasise uniform heat distribution, controlled combustion, and reduced smoke production [20]; [21]. Design principles common to both cookstoves and grill stoves include efficient air–fuel mixing, adequate insulation, and effective heat transfer to the cooking surface. Incorporating these principles into biomass stove design is essential to achieving cleaner, more efficient operation, particularly when multiple functions are integrated into a single device (Figure 2).

Figure 2: Different open-fire grill stoves designs [23]

2.3. Improved Biomass Cookstoves and Research Gaps

Improved biomass cookstoves incorporate scientific principles of thermodynamics, combustion, and heat transfer to enhance performance [24]-[26]. Technologies such as rocket stoves, gasifier stoves, and hybrid designs have demonstrated significant reductions in fuel consumption and emissions compared to traditional stoves. Chimney-equipped stoves, in particular, are effective in reducing indoor smoke exposure by venting combustion products outdoors. Despite these advancements, several gaps remain in current research and practice. Many improved stoves are designed for a single function, limiting their versatility. In contexts where grilling is common, users often revert to open fires or separate grills, negating some of the benefits of improved cooking technologies. Additionally, performance evaluation often focuses solely on cooking efficiency, with limited attention to grilling performance. This study contributes to the literature by addressing these gaps through the design and evaluation of a dual-purpose biomass cookstove that integrates cooking and grilling functions. By assessing both numerical thermal behaviour and experimental performance, the work provides a more comprehensive evaluation of multifunctional biomass stove technology.

3. Materials and Methods

The dual-purpose biomass cookstove was designed and fabricated using locally available materials to promote affordability, ease of maintenance, and local manufacturability. Mild steel was selected as the primary construction material due to its availability, strength, and favourable thermal properties, with sheet thicknesses of 1.5–2 mm for major components and a mild steel pipe for the chimney. Fabrication involved marking, cutting, rolling, welding, and finishing, with gauge-12 electrodes ensuring durable joints. Hinges and a detachable ashtray were incorporated to improve usability, cleaning, and airflow control.

The stove was designed to operate with wood and charcoal, taking into account fuel characteristics, calorific value, airflow, combustion chamber geometry, safety, and household cooking needs for a family of six. Numerical analysis was carried out using ANSYS transient thermal simulations based on a SolidWorks model to evaluate temperature and heat flux distributions. The experimental evaluation included water-boiling and grilling tests to assess thermal efficiency, heat distribution, and overall performance, with results compared to existing cookstove data in the literature.

3.1. Design Calculations

3.1.1. Fuel Energy Input

The total energy released from the biomass fuel during combustion is given by:

$$Q_{in} = m_f \times CV \quad (1)$$

Where:

- $\mathbf{Q_{in}}$**:** Heat Energy Supplied by the Fuel (J)
- $\mathbf{m_f}$**:** Mass of Biomass Fuel Consumed (kg)
- **CV:** Calorific Value of the Biomass Fuel (J/kg)

3.1.2. Useful Heat Gained by Water (Cooking Mode)

The useful heat absorbed by the cooking water during the water boiling test is calculated as:

$$Q_{useful} = m_w c_w (T_b - T_i) \quad (2)$$

Where:

- $\mathbf{m_w}$**:** Mass of Water (kg)
- $\mathbf{c_w}$**:** Specific Heat Capacity of Water (4186 J/kg·K)
- $\mathbf{T_b}$**:** Boiling Temperature of Water (°C)
- $\mathbf{T_i}$**:** Initial Water Temperature (°C)

3.1.3. Thermal Efficiency of the Cookstove

The thermal efficiency of the biomass cookstove is defined as the ratio of useful heat gained to the energy released by the fuel:

$$\eta = \frac{Q_{useful}}{Q_{in}} \times 100 \quad (3)$$

or equivalently:

$$\eta = \frac{m_w c_w (T_b - T_i)}{m_f \times CV} \times 100 \quad (4)$$

Where:

- $\boldsymbol{\eta}$**:** Thermal Efficiency of the Cookstove (%)

3.1.4. Rate of Heat Transfer

The rate of heat transfer during cooking or grilling is expressed as:

$$\dot{Q} = \frac{Q}{t} \quad (5)$$

Where:

- $\dot{\mathbf{Q}}$**:** Heat Transfer Rate (W)

- **Q:** Total Heat Transferred (J)
- **T:** Time Taken (s)

3.1.5. Heat Flux Estimation

The heat flux across the cooking or grilling surface is determined using:

$$q'' = \frac{\dot{Q}}{A} \tag{6}$$

Where:

- $\mathbf{q''}$**:** Heat Flux (W/m²)
- **A:** Effective Heat Transfer Area (m²)

3.1.6. Fuel Consumption Rate

The rate of fuel consumption is evaluated as:

$$\dot{m}_f = \frac{m_f}{t} \tag{7}$$

Where:

- $\dot{\mathbf{m}}_{\mathbf{f}}$**:** Fuel Consumption Rate (kg/s)

3.1.7. Power Output of the Cookstove

The average thermal power output of the stove is given by:

$$P = \dot{m}_f \times CV \tag{8}$$

Where:

- **P:** Thermal Power Output (W)

3.1.8. Grilling Performance Relation

For grilling tests, the relationship between grilling time and meat thickness can be expressed empirically as:

$$t_g \propto d_m \text{ or in linear form, } t_g = kd_m \tag{9}$$

Where:

- $\mathbf{t_g}$**:** Grilling Time (s)
- $\mathbf{d_m}$**:** Meat Thickness (cm)
- **k:** Proportionality Constant Dependent on Heat Flux and Material Properties

3.2. Conceptual Design of the Biomass Cookstove

The conceptual design of the biomass cookstove was modelled using Autodesk Fusion 360, and the full assembly is shown in Figure 3:

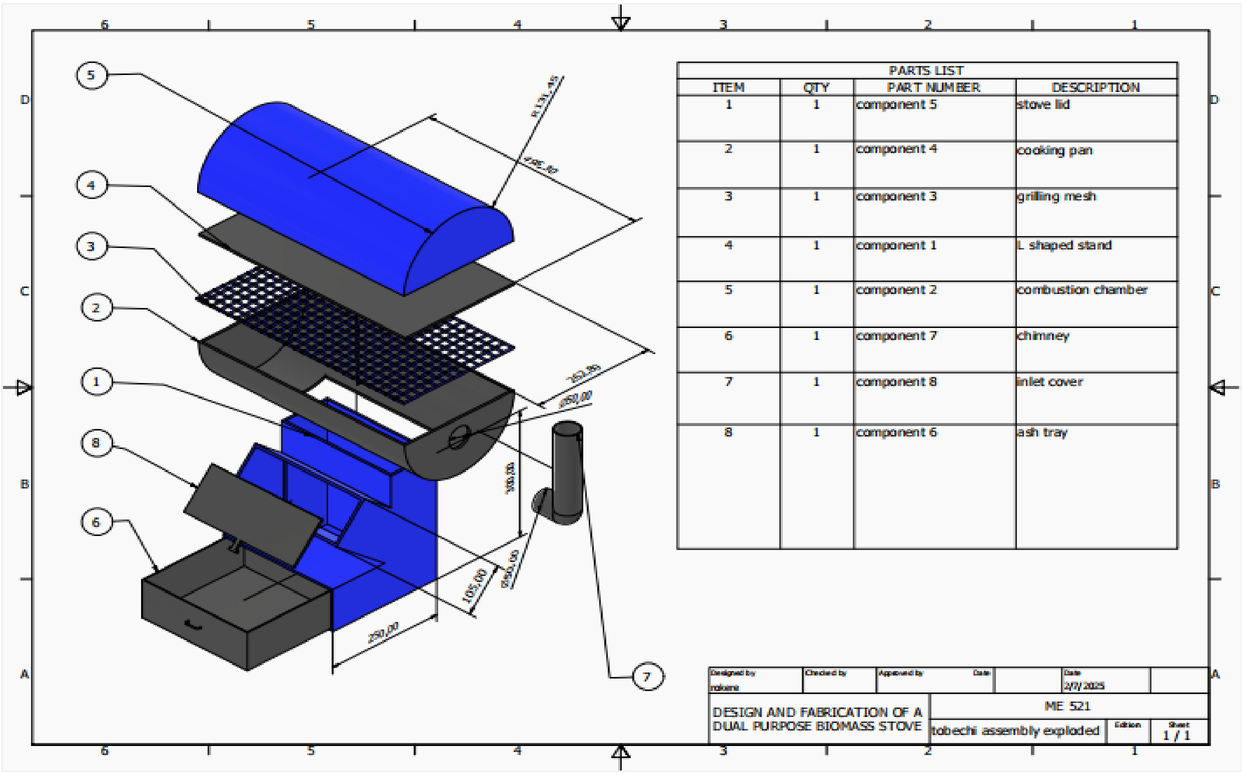

Figure 3: Full assembly of the constructed dual-purpose biomass stove design

Figure 4 shows the experimental prototype of the made-up heating unit. It has a horizontal cylindrical combustion chamber and a vertical exhaust chimney for flue gas discharge. Figure 4 shows that the system is installed on a sturdy metal frame with a feeding input and a collection tray. It is intended for controlled thermal processing in the field.

Figure 4: Image of fabricated cookstove

3.3. Transient Thermal Analysis

Transient analysis results enable the evaluation of how temperature and heat flow evolve with time within a system, capturing the dynamic thermal response during heating and cooling processes under realistic operating conditions. Unlike steady-state thermal results, transient analysis provides insight into time-dependent thermal behaviour, which is critical for assessing performance during start-up and continuous operation. In this study, ANSYS software was used to conduct a transient thermal simulation to assess the workability and thermal performance of the biomass cookstove before fabrication. This simulation enabled the prediction of temperature distributions, heat flux patterns, and potential thermal hotspots, thereby informing design decisions and reducing the risk of material failure or inefficient operation during practical use.

4. Results and Discussion

4.1. Simulations Results

4.1.1. Discretization

Figure 5 shows the finite-element mesh of the biomass cookstove. It shows the discretised geometry used for structural and thermal analysis.

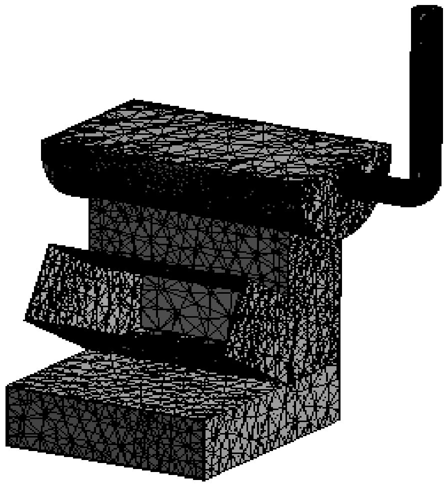

Figure 5: Mesh model

Figure 5 shows that the model has a precise triangulated mesh of the combustion chamber, support structure, and exhaust chimney. This makes it easier to run numerical simulations and test performance (Table 1):

- **Element Order:** Tri-mode Nodes
- **Quality:** Mechanical
- **Smoothing:** Medium.

Table 1: Mesh model details

Quantity	Model
Number of Nodes	194599
Number of Elements	96433

4.1.2. Boundary Condition

Figure 6 shows the loading conditions applied to the cooking stove to assess its behaviour. Figure 7 shows the temperature distribution on the heating plate of the cookstoves used for cooking and grilling from 120 to 480 seconds. At 120 s, heat is mainly concentrated around the combustion chamber and cooking plate, with a maximum temperature of about 40 °C. Limited heat transfer to the chimney indicates an early heating stage and gradual thermal build-up. At 240 s, temperatures across the stove body rise to approximately 61 °C. Heat begins to propagate toward the chimney, showing improved convective heat transfer and a reduced temperature gradient within the structure. By 360 s, peak temperature increases to about 81 °C, with enhanced heat distribution over the cooking surface. The chimney shows increased thermal activity, indicating sustained combustion and improved draft performance. At 480 s, the stove approaches a quasi-steady condition with a maximum temperature of about 101 °C. Heat distribution becomes more uniform, confirming effective thermal management and suitability for prolonged operation. The transient simulation shows a consistent, stable increase in temperature over time, validating the cookstove's thermal workability before fabrication.

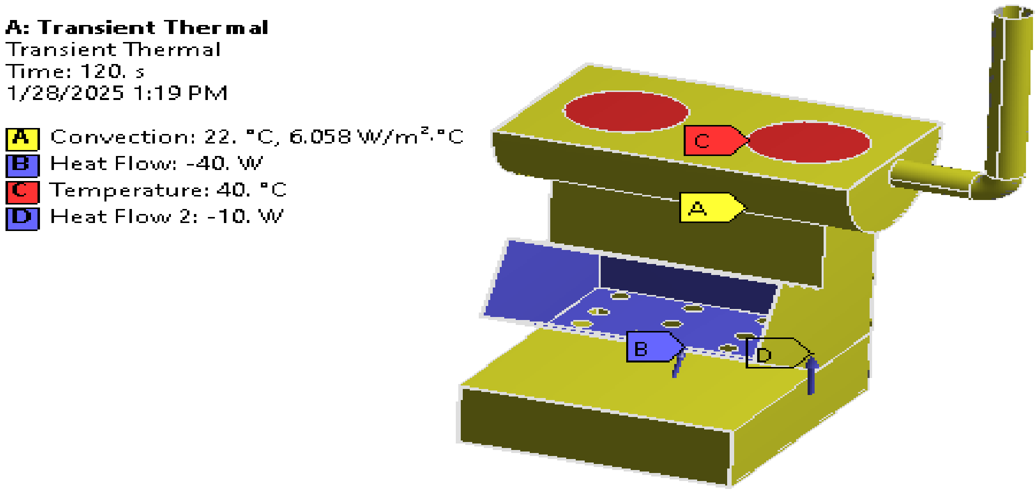

Figure 6: Boundary condition for transient thermal analysis

The results confirm efficient heat transfer, controlled chimney performance, and the suitability of mild steel for sustained thermal operation.

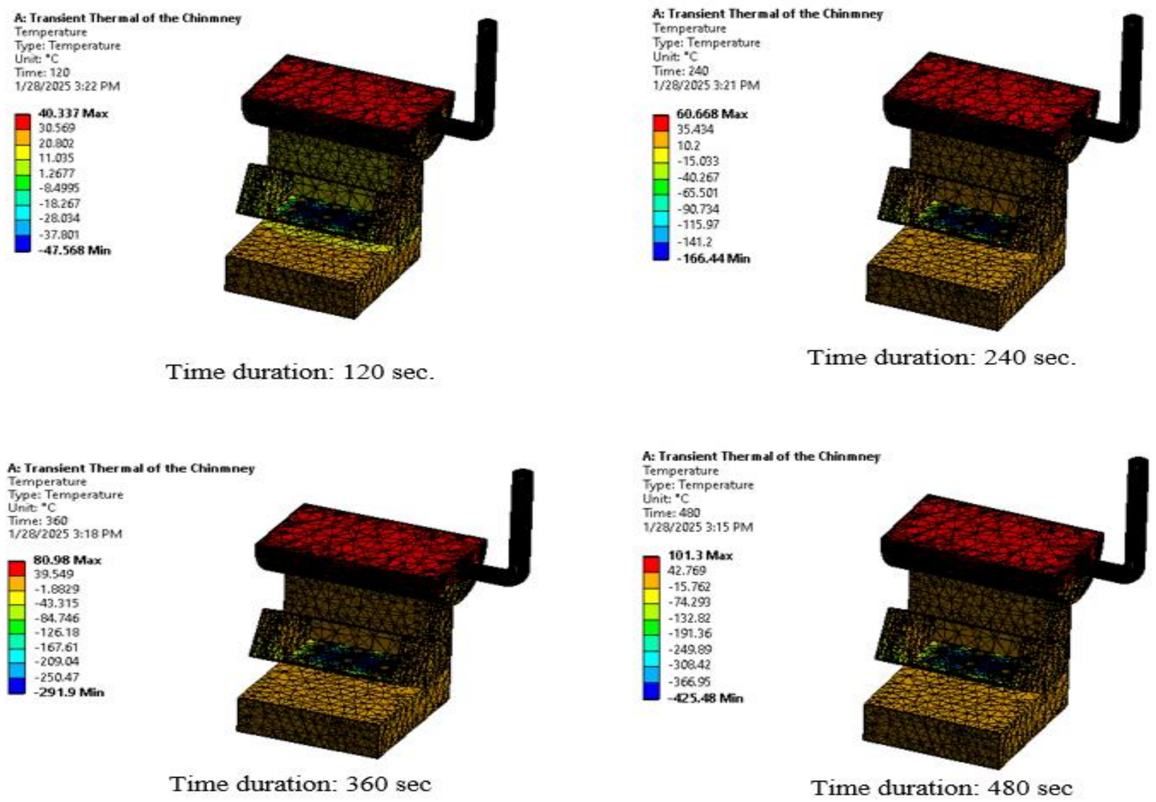

Figure 7: Temperature distribution from 120 seconds to 480 seconds

4.2. Experimental Results

Table 2 shows that the heat flux increases over time, with minimum, maximum, and average values rising from 120 s to 600 s. The widening gap between minimum and maximum flux indicates non-uniform heat distribution. In contrast, the steady rise in average flux reflects overall system heating, highlighting transient thermal behaviour before steady state.

Table 2: Results of heat flux variations against time

Time (sec)	Min. (W/m^2)	Max. (W/m^2)	Average (W/m^2)
120	2.0637e-005	1.2888e+005	4513.1
240	5.886e-005	3.3231e+005	10014
360	1.3948e-004	5.4389e+005	15751
480	6.8066e-004	7.6555e+005	21694
600	8.3092e-004	9.8989e+005	27739

Table 3 presents the water boiling test results for volumes ranging from 1 to 5 litres. Boiling time increases consistently with water volume, from 18 minutes 28.5 seconds for 1 litre to 53 minutes 16.5 seconds for 5 litres. The close agreement between Test 1 and Test 2 indicates repeatability, and converting to seconds enables precise comparison of heating performance, highlighting the system's capacity to handle larger water volumes.

Table 3: Results of water boiling test

Volume of Water	(Test 1) Boiling Time (Minutes)	(Test 2) Boiling Time (Minutes)	Average Boiling Time (Minutes)	Average Boiling Time (Seconds)
1 litre	18mins 50seconds	18mins 07seconds	18mins 28.5sec	1108.5
2 litres	27mins 40seconds	27mins 14seconds	27mins 27.0sec	1647.0
3 litres	35mins 14seconds	35mins 16seconds	35mins 15.0sec	2115.0
4 litres	46mins 19seconds	45mins 55seconds	46mins 07.0sec	2767.0
5 litres	53mins 43seconds	53mins 20seconds	53mins 16.5sec	3196.5

Table 4 shows the grilling test results for meat samples of varying thickness. Grilling time increases with sample thickness, from 1400.06 seconds for 3 cm to 2960.92 seconds for 7 cm, indicating a direct relationship between thickness and cooking duration. The data highlights that thicker samples require significantly more heat exposure to cook thoroughly, emphasising the importance of adjusting grilling time based on meat thickness for consistent cooking and food safety.

Table 4: Grilling test results

Thickness of Grilled Meat Sample (cm)	Grilling Time (Seconds)
3	1400.06
4	1509.16
5	1897.76
6	2590.87
7	2960.92

5. Conclusion

This study successfully designed, fabricated, and evaluated a dual-purpose biomass cookstove capable of performing both cooking and grilling functions using wood and charcoal fuels. The combination of numerical thermal analysis and experimental testing provided a comprehensive assessment of the stove's performance. The transient thermal analysis confirmed stable temperature rise and effective heat flux distribution, indicating that the stove design supports sustained thermal operation. Experimental results from water boiling and grilling tests demonstrated that the stove performs satisfactorily for domestic applications, with acceptable cooking and grilling times. Although the performance was slightly lower than that of open-fire and average grill stoves, the improved emission control achieved through the chimney system significantly reduces household air pollution. This trade-off highlights the importance of prioritising health and environmental benefits alongside cooking speed. The use of locally available materials and simple fabrication techniques enhances the feasibility of local production and adoption, particularly in rural and peri-urban communities. By integrating cooking and grilling functions, the stove reduces the need for multiple devices, potentially lowering overall fuel consumption and costs. In conclusion, the dual-purpose biomass cookstove represents a viable, low-cost, and sustainable household energy solution. Future work should focus on improving insulation to reduce heat losses, optimising airflow for faster cooking, and conducting emission measurements to quantify environmental benefits more precisely. With further refinement, the proposed stove design has strong potential to contribute to cleaner cooking initiatives and improved quality of life in biomass-dependent communities.

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Ethics and Consent Statement: All experimental activities were conducted in accordance with established ethical guidelines. Appropriate approvals and permissions were obtained before the study, and informed consent was obtained from involved stakeholders where applicable.

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