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Design and Development of a High Efficiency Briquette-Fired Adjustable Stove

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ABSTRACT
This study focuses on the design, fabrication, and performance evaluation of a biomass briquette-fired adjustable stove. The stove was developed using locally sourced materials. In addition, groundnut shells were used as biomass while cassava starch was used as a binder to address the challenges of rising cooking fuel costs and environmental sustainability. Key design features include an adjustable combustion chamber, effective fiberglass wool insulation, and cost-effective construction. Performance evaluations revealed a high thermal efficiency of 70.03%. Furthermore, a specific fuel consumption of 0.294 kg/kg and a burning rate of 0.426 kg/h were recorded. The stove demonstrated superior efficiency compared to traditional and some modern stoves, reflecting optimized combustion and heat transfer.

KEYWORDS: Water Boiling Test, Renewable Energy, Sustainable Energy,Thermal Efficiency, Biomass Cookstove.

I. INTRODUCTION

In a country where the cost of fossil fuels for domestic use has skyrocketed beyond the reach of many Nigerians living in rural and suburban areas, exploring renewable energy sources as alternatives for household use is crucial. Since fossil fuels are non-renewable, the focus must shift to sustainable energy options. Researchers have been studying biomass for over four decades due to its renewable nature, abundance, and positive environmental impact. To protect the ecosystem, deforestation should be strictly discouraged, and attention should instead be directed toward other renewable energy sources, such as agricultural waste products[1] and [2]. The need to explore alternative energy sources is driven by several factors, these factors include the continuously rising prices of kerosene and cooking gas in Nigeria, the household sector's heavy reliance on energy, which has led to significant shortages of wood and charcoal in both rural and urban areas, and the insecurity in the northern region of the country, which poses challenges to accessing coal and wood from forests[3]. Briquettes are an excellent illustration of a substitute energy source. This is because briquettes are incredibly inexpensive [4]. Biomass energy is a source of energy that can be harnessed in homes for heating and cooking. It is cheap, safe, easily available, and easy to use. Biomass materials like groundnut shells [5], palm kernels [6], millet and wheat straws, sorghum stalks, maize stalks, corn cobs [7], cotton wastes, sugarcane bagasse, and water hyacinth [8] can be transformed into fuel briquettes for direct burning to generate heat for cooking. These agricultural wastes are produced throughout various stages, including land preparation, planting, harvesting, processing, packaging, transportation, and consumption [9]. When decomposing biomass from abandoned agricultural wastes is washed into neighboring water bodies by rainfall, it pollutes the water. People contract cholera and other water-borne illnesses when they drink this water [10].

Briquettes are compressed blocks or solids of combustible biomass materials used as fuel and for kindling fire [11]. They are made by densifying organic fibers at low pressure after mixing them with a suitable binder. The common biomass briquettes used are ellipsoidal, perforated, or hollow cylinders and cylinders [12].

A World Health Organization (WHO) report reveals that approximately 3 billion people rely on open flames fueled by biomass such as wood, animal dung, agricultural residues, and coal for cooking. This practice leads to over 4 million premature deaths annually due to household air pollution from solid biomass fuel use [13]. It is vital to offer clean energy and hygienic cooking in this situation. Biomass briquette stoves have emerged as a promising solution to address these multiple global challenges, such as environmental sustainability, public health, and energy access. However, the adoption of briquettes is limited by the lack of efficient and affordable stoves designed to maximize their performance.

This study focuses on developing a high efficiency briquette-fired adjustable powered by briquettes made from groundnut shells and cassava starch as a binder that addresses these challenges by combining high thermal efficiency with user-friendly design features. The objective is to create a stove that is cost-effective, environmentally sustainable, and versatile for various cooking needs.

The rising cost and intermittent shortages of cooking fuels have pushed low-income populations in developing countries to depend heavily on traditional fuels like charcoal and firewood, often without considering their environmental consequences [14]. This situation has prompted researchers to explore alternative energy sources and spurred engineers and technicians to design and construct efficient cooking systems. These systems aim to reduce the consumption of wood and coal, minimize resource depletion, and mitigate the associated environmental and health impacts [15]. According to [16], energy efficiency is closely linked to energy conservation, as efficient stoves can conserve energy, lower costs, and reduce harmful emissions. The development and promotion of energy-efficient technologies enhance living standards and contribute to poverty reduction [14]. Developing countries face a severe energy crisis, with many rural residents relying solely on biomass for energy [17]. In Africa, a significant portion of wood harvested from forests is either used directly as firewood or converted into charcoal [14]. More than 80% of the coal consumed is used in urban areas, making it a primary domestic energy source in many African cities [16]. Globally, around 2.4 billion people rely on wood, manure, coal, and other biomass fuels for cooking [18]. In Nigeria alone, over 24 million households use wood exclusively as a cooking fuel [14]. This traditional method of cooking poses severe health risks, often referred to as a "silent killer" [14]. Extensive research has been conducted on stove design and development. While open fires can convert up to 90% of wood into energy, only a fraction—typically between 10% and 40%—of this energy is effectively transferred to the cooking vessel [14]. Enhancing heat transfer efficiency to the cooking pot has a more significant impact on reducing fuel usage than improving combustion efficiency alone. Nonetheless, improving combustion efficiency remains essential to reduce smoke and harmful emissions that pose risks to human health [14].

Today, commonly used domestic cookstoves worldwide can be generally categorized into two groups, namely: combustion cookstoves and non-combustion cookstoves. Cookstoves that operate by directly burning solid, liquid, or gaseous fuels, converting the chemical energy of the fuel into thermal energy, are known as combustion cookstoves. Examples include biomass cookstoves, gas cookstoves, kerosene cookstoves, charcoal cookstoves, and their variants. On the other hand, non-combustion cookstoves do not involve the burning of fuels; instead, they convert solar or electric energy into thermal energy. Examples of non-combustion cookstoves are solar cookers, electric cookstoves, induction cooktops, and their variants.

In terms of advancements in biomass cookstoves over recent decades, they can be categorized into three main types: traditional cookstoves, improved cookstoves, and advanced cookstoves. Biomass cookstoves are further classified as stationary (non-metal cookstoves) and portable (metal cookstoves), natural draft (buoyancy-driven), and forced draft (fan or blower-driven). Advanced biomass cookstoves fall into two categories: combustion cookstoves and gasifier cookstoves. For a more detailed classification of biomass cookstoves, refer to the literature. [19],[20], and [21].

II. MATERIALS AND METHODS

2.1 Design Considerations

The stove was designed with the following priorities:

Ease of Manufacture: Simplified design for construction by local artisans.

Thermal Efficiency: Fiberglass insulation minimizes heat loss, and lightweight materials enhance heat transfer. There is a strong relationship between stove efficiency and weight [22]. The efficiency of a stove decreases with weight and increases with lightness [22]. Using this premix, a portable stove was created. The stove's thermal efficiency was increased by insulating the wall with fiberglass.

Adjustability: An adjustable briquette pot allows optimized combustion for various cooking needs.

Cost-Effectiveness: Local materials like mild steel and galvanized sheets were used to ensure affordability.

2.2 Design Calculations

The volume of the briquette chamber

The volume of the chamber is expected to be higher than that of the briquette biomass. Therefore,

$$V = \frac{1}{3}h(a^2 + b^2 + ab) \quad \text{.........(1)}$$

a = lower base length = 150 mm
b = upper base length = 200 mm
h = height of the of the chamber = 180 mm

$$V = \frac{1}{3} \times 180(150^2 + 200^2 + (150 \times 200))$$

$V = 5{,}550{,}000\ mm^3$

Volume of Chamber= $5{,}550{,}000\ mm^3$,

Stress on the stove

The stress developed in the stove structure can be computed through the following steps.

Force on stove =m x a.........(2)
m = mass of pot and content
a = acceleration = $9.81 m/s^2$

Therefore, the force on the stove is Force = 25 x 9.81= 245.25N

Area of Briquette stove = 100 x 350 + [(350 x 250) – (300 x 200)]
= $62{,}500\ mm^2$

Therefore,

$$\text{Stress on Stove} = \frac{\text{Force}}{\text{Area}} \quad \text{.........(3)}$$

$$\text{Stress on Stove} = \frac{245.25}{62{,}500}$$

Stress on the Stove = $0.0039\ N/mm^2$

Since stress on the stove is less than the allowable stress on the stove structure (137.5MPa) according to the [23], the design is suitable.

2.3 General design specifications

The Briquette pot/carrier

This is a $5{,}550{,}000\ mm^3$ perforated mild steel enclosure designed to accommodate a briquette. The perforated briquette pot or combustion chamber allows for free air intake for proper combustion and the passage of ashes produced during the combustion. It is a truncated pyramid in shape. It has a lower base of length 15cm, an upper base length of 20 cm, and a height of 18cm.

Plate 1: Shows the briquette pot.

Stove body

The body is made of a mild steel sheet formed into a cube with the following dimensions:
Length = 35 cm
Breadth = 35 cm
Height = 35 cm

The cube is made of two chambers. The first chamber carries the briquette pot consists of an inner cuboid and the outer cuboid forms a heat conservation chamber with a wall thickness of 2.5 cm which was filled with fiberglass wool to minimize heat loss by conduction and the other chamber for the screw jack to control the upward and downward movement of the briquette pot. Plate 2shows the chambers of the fabricated stove.

Plate 2: Shows the body of the stove with a screw jack in the second chamber.

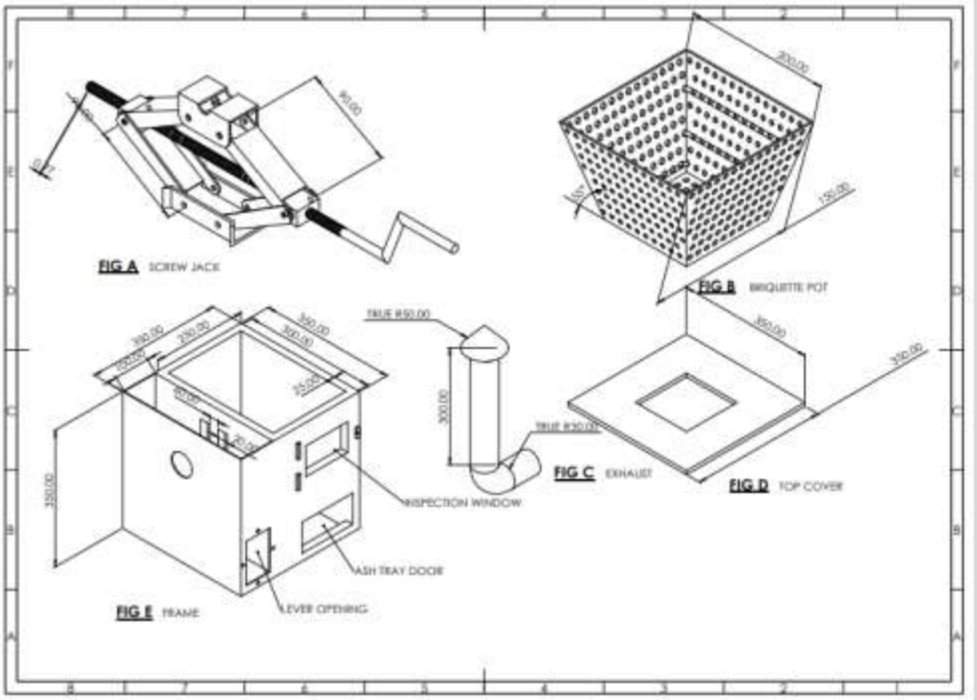
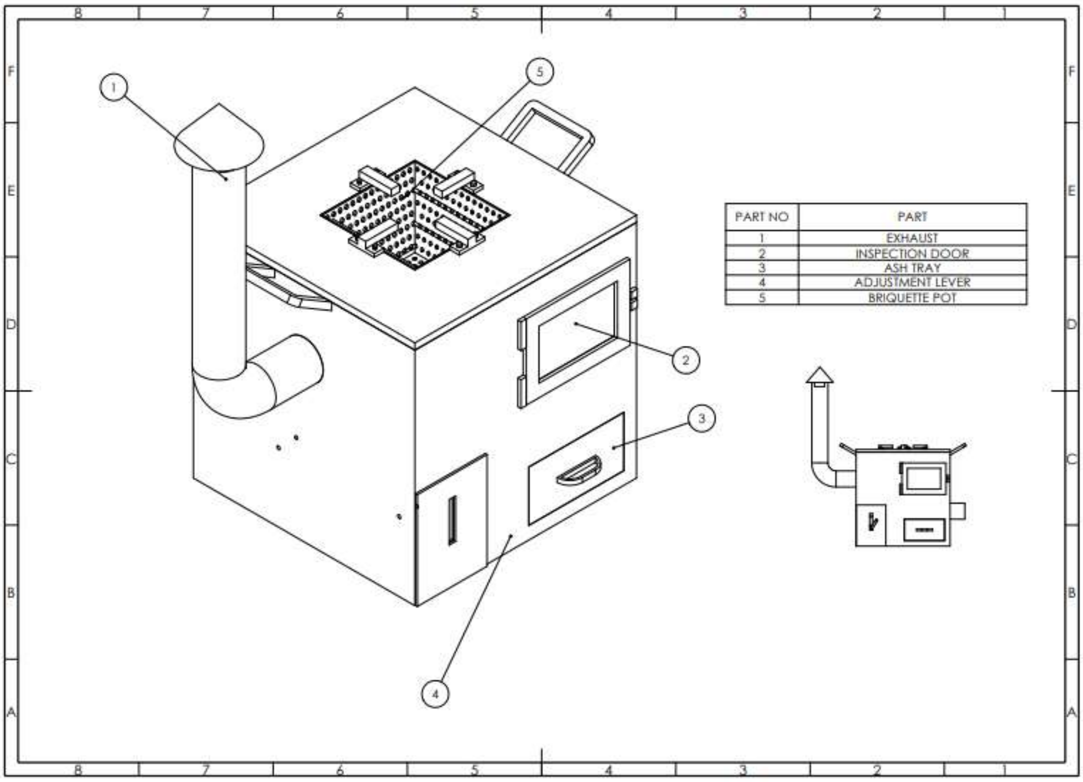


Figure 1: Parts of the briquette-fired adjustable stove



PART NO	PART
1	EXHAUST
2	INSPECTION DOOR
3	ASH TRAY
4	ADJUSTMENT LEVER
5	BRIQUETTE POT

Figure 2: Isometric projection of the stove

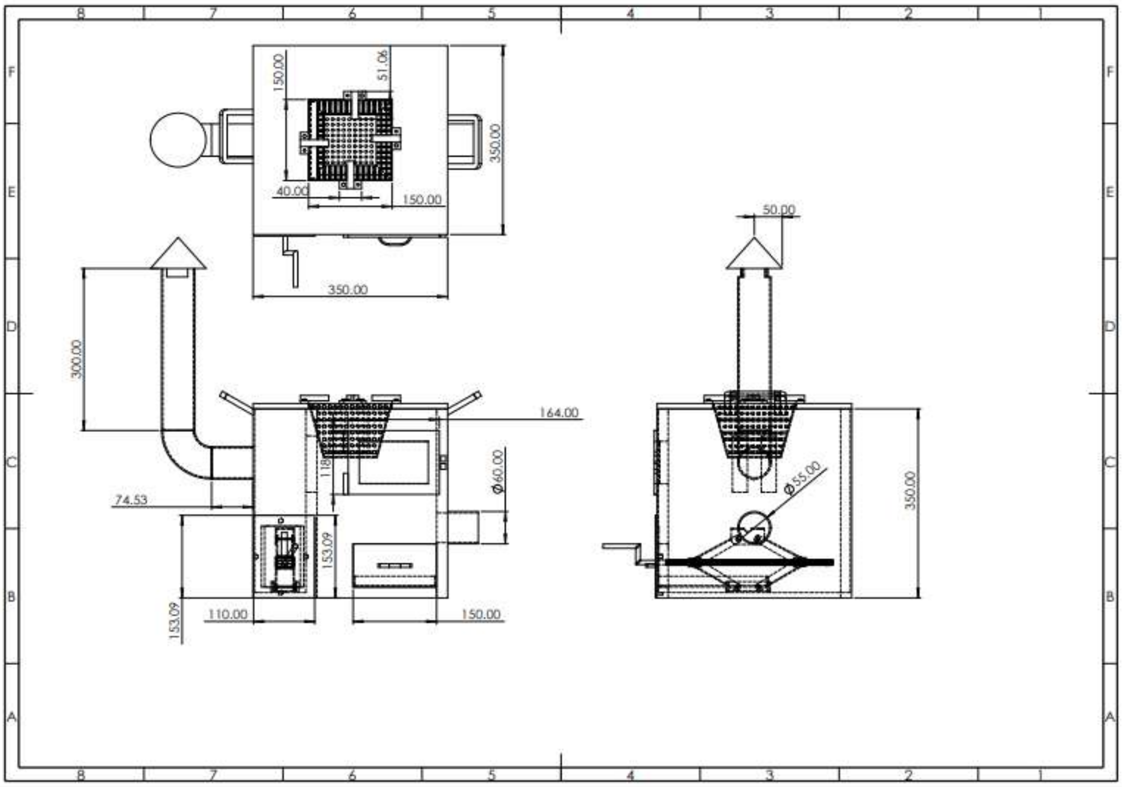


Figure 3: Orthographic projection of the stove

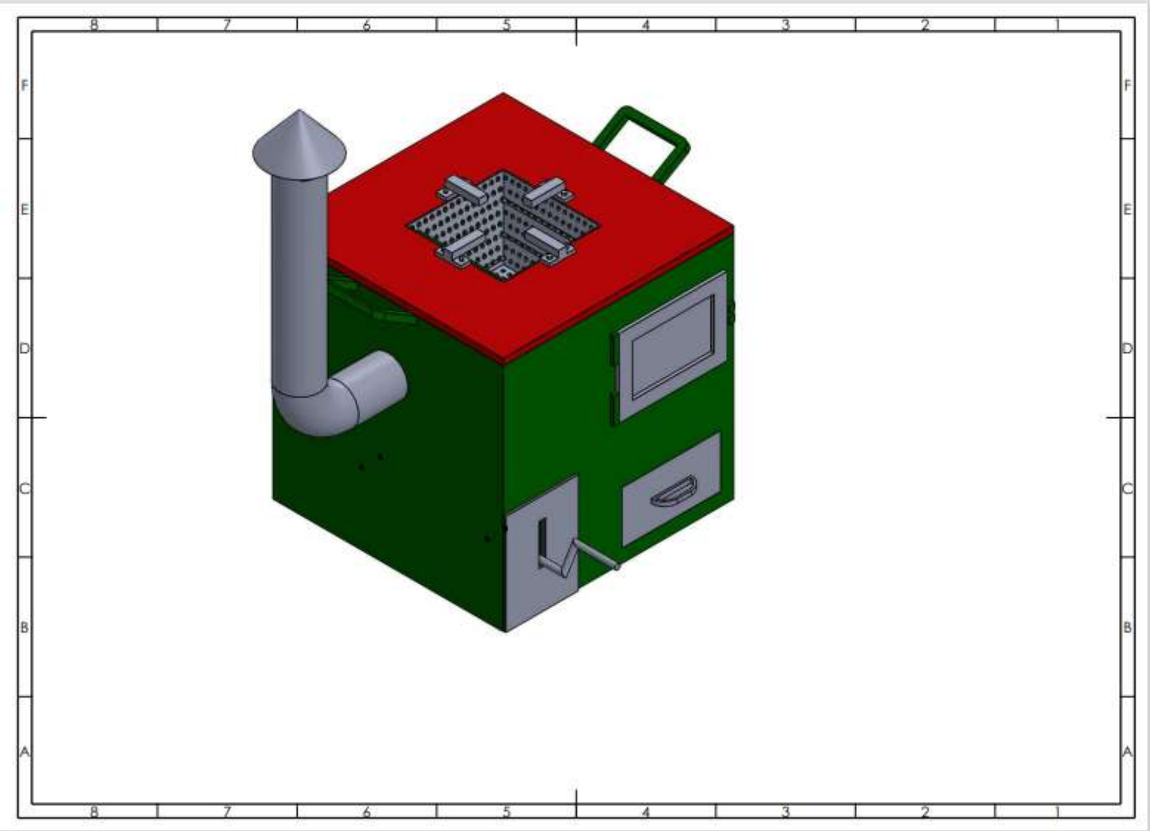


Figure 4: Isometric Projection of the stove

Chimney

This component is constructed from a mild steel pipe and a galvanized sheet, folded into a pipe with a diameter of 70 mm. It extends from the heat conservation chamber, passes through the insulated wall to the atmosphere, and functions as the channel for expelling burnt gases.

Plate 3: Shows the chimney pipe.

2.4 Design and fabrication of the stove.

To produce the briquette-fired adjustable stove in this work, the stove was designed using the standard SolidWorks program, as indicated in Figures1 to 4. The stove was fabricated following efficient design, measurement, marking out, cutting, chiseling, bending, welding, riveting, bolting of the screw jack to the base of the stove, and finishing. The following equipment/tools were used to produce the briquette-fired adjustable cookstove: hacksaw, steel rule, snip, bending machine, welding machine, scriber, divider, clamp and bench, and hammer. The metal sheet utilized to achieve the production is the mild steel metal sheet. The stove body, ashtray, chimney for appropriate smoke emission, and briquette pot or carrier comprise the entire stove. The developed stove is shown in plate 4.

Plate 4: Complete fabrication of the briquette-fired adjustable stove

2.5 Briquette production

This study is interested in the production of briquettes in rural areas. Waste groundnut shells and cassava starch were used for the briquettes in this study because they are easily accessible in Northern Nigeria, where the issue of desert encroachment is more severe [24]. Additionally, due to its fibrous character, it is probably going to behave similarly to another fibrous organic residual matter during the densification process [24]. In rural areas, this kind of material is more likely to be accessible for briquetting. After being gathered, groundnut shells were mashed with a pestle and mortar, sieved, and let to dry in the sun for five days. The particles used were those that made it past the sieve. Water was added to the ground-up starch, and the sieved groundnut shell was then manually stirred in until the mixture was well combined. An existing briquette-making machine was then used to create the briquettes. The machine is a manually controlled die-heated briquette-making equipment that manufactures briquettes. Before being used in the manufactured briquette adjustable stove, the prepared briquettes were sun-dried for twenty (20) days.

III. THE STOVE PERFORMANCE EVALUATIONS

3.1 Test procedure

To conduct the water boiling test, the following procedures were followed: The briquette fuel to be used was measured (kg), the pot was thoroughly cleaned and dried and the mass of the empty pot was also noted, and then the pot was filled with 2.5 kg of water. The initial temperature of the water was also recorded, and the briquettes were arranged in the briquette combustion chamber of the stove with the briquette fuel of 0.75 kg, which was ignited with 10ml in volume of kerosene, and the inspection door and ashtray of the stove were left open to allow enough oxygen for effective burning of the briquette fuel. After some time, they were all shut to allow adequate combustion of the briquette in the briquette pot in a confined well-insulated chamber. It was ensured that there was sufficient briquette fuel available for the test. The pot was placed on the stove the moment the briquettes started burning. The time of the day and the initial temperature of the water were recorded. The temperature of the water was recorded at intervals of five (5) minutes until the moment the water came to a vigorous boil. The pot was then removed from the stove and the fire was immediately put out with the help of dry sand. The final weight of the remaining water, fuel, and the final temperature of water were then measured and recorded and were used for the calculations.

The apparatus used for the tests includes one medium-sized aluminum pot, a weighing scale, a stopwatch, a lighter, and a thermometer. The performance evaluation of the cook stove was carried out to examine its specific fuel consumption, time spent, burning rate, and thermal efficiency, utilized heat.

Plate 5: Measuring the mass of water and fuel during performance evaluation.

3.2 Thermal efficiency

The thermal efficiency of a cooking stove is primarily influenced by how effectively heat is transferred from the combustion point to the pot [25]. To reduce heat losses and enhance heat transfer, the distance between the fuel bed and the pot was minimized. The calculation followed the procedure and formula outlined in [26].

From equation (3),

M_w = Initial mass of water in the pot = 2.5kg

C = Specific heat capacity of water = 4.2 $\text{kJ kg}^{-1}\text{ K}^{-1}$

t_2 = Final temperature of water = 102°C

t_1 = Initial temperature of water = 33°C

Ms = Mass of water evaporated during experiment = 0.51kg

L = Latent heat of evaporation of water = 2260kJ kg^{-1}

Mf = Mass of fuel used = 0.15kg

CV = Lower calorific value of fuel = 17869kJ kg^{-1} [27]

$$E=\frac{MwxCx\ (t2-t1)+MsxLx\ \ 100}{MfxCV} \qquad \text{...}(4)$$

$$E = \frac{2.5 \text{ x } 4.2 \text{ x } (102-33)+0.51 \text{ x } 2260 \text{ x } 100}{0.15 \text{ x } 17869}$$

E = 0.7003 x 100

Thermal Efficiency = 70.03%

3.3 Burning rate

This is a measure of the rate of wood consumption while bringing water to a boiling point [28]. The formula used in the calculation was based on the approach used by [29].

Tests on the burning rate were carried out with the briquette-fired adjustable stove. The final weight of fuel at the end of the test and the time taken to burn were recorded. From equation (2):

$$Br= \frac{W_1-W_2}{T} \qquad \text{..}(5)$$

W_1 = 0.75kg
W_2 = 0.60kg
T = 21mins
Br= $\frac{0.75-0.60}{21}$
The burning rate = 0.0071kg.min^{-1}
Br = 0.426kg.hr^{-1}

3.4 Time spent in boiling

The time spent in boiling in the water is calculated using the relationship below:

Time spent = $\frac{\text{Total time in boiling water}}{\text{Total mass of boiled water}}$..(6)

Time spent = $\frac{T}{Mw}$

Time spent = $\frac{21}{2.5}$

Time spent = 8.4mins/Kg

Specific Fuel Consumption (SFC)

SFC=$\frac{Mf}{Ms}$ ....(7)

Where:
Ms = mass of water evaporated = 2.50 – 1.99 = 0.51Kg
M_f = mass of fuel used = 0.75 – 0.60 = 0.15Kg
SFC = Specific Fuel Consumption
SFC = $\frac{0.15}{0.51}$
SFC = 0.294Kg/Kg

3.5 Utilized heat

This study adopted the methods and equations outlined by [30] to calculate the heat value. The heat of the briquettes was evaluated by testing them on a stove. Specifically, the briquettes were used to boil 2.50 kg of water. The initial and final masses of the briquettes, as well as the water temperature from the start to the end of the process, were recorded. The heat value was determined using the following formulas:

$\mathbf{Q_s}$ = M_w x C x ΔT ....(8)

Where:
Qs = Sensible heat KJ
C = Specific heat of water kJ kg^{-1} K^{-1}
M_w = Water mass, in kilograms
ΔT = Temperature change (k) [30]
Qs = 2.5 x 4.2 x (102 - 33)
Qs = 724.5 KJ

Value of Heat, q = $\frac{\mathbf{Q_s}}{Mf}$...(9)

Where:
Qs = Sensible heat (kJ)
Mf = Mass briquette fuel used (Kg) [30]
q = $\frac{724.5}{0.15}$
Value of Heat, q = 4,830 KJ/Kg

3.6 Cost analysis of the cookstove

The production cost of the stove comprises the material cost, labor cost, and overhead cost, with the material cost breakdown detailed in Table1.

Labor cost

The labor cost was determined based on the total man-hours required for the development of the cookstove. The production process spanned two weeks, during which all materials were procured. The manufacturing was completed within one week, with the remaining days dedicated to aesthetic finishing. The work schedule consisted of five working days per week, with 4 hours of labor per day. The total man-hours spent are calculated as follows:

Man-hour = 2 × 4 × 5 × 2 = 80 man-hours.

Each hour is rated ₦440. Therefore, labor cost = 80 × 440 = 35,200 = ₦35,200

Overhead cost

This is 30% of the sum of material and labor costs.

Overhead cost = 30% [material + labor cost] = 0.3[41,600 + 35,200]

Overhead cost = 0.3[76,800] = ₦23,040

The total cost of producing the cookstove is the summation of the three-component cost.

The total cost of production = material + labor + overhead cost = [41,600 + 35,200 + 23,040] = ₦99,840

The total cost of production is ₦99,840

Table 1: Material, Labor, and Overhead Costs

S/N	Materials	Size	Quantity	Unit Price (₦)	Cost (₦)
1	Mild Steel	600mm x 1200mm x 1.5mm	1	7,500	7,500
2	Galvanized Sheet	300mm x 600mm x 1mm	1	4,500	4,500

3	Screw Jack	Standard	1	3,700	3,700
4	Mild Steel	150mm x 300mm x 5mm	1	5,000	5,000
5	Rivet Pin	Standard	8	250	2,000
6	Mild steel electrodes	Standard	1 Pkt	7,000	7,000
7	Bolts and nuts	M10	8	100	800
8	Fiber Glass Wool	1 Yard	1	7,000	7,000
9	Hinches	Standard	2	300	600
10	Oil Paint		1 litre	3,500	3,500
12	Labor		--	35,200	35,200
13	Overhead		--	23,040	23,040
	Grand Total				**99,840**

IV. RESULTS AND DISCUSSION

4.1 Results and discussion on the design of the stove

The stove was designed using SolidWorks software, ensuring precise modeling and visualization of the components.

The volume of the briquette chamber

The volume of the chamber is 5,550,000 mm³. This volume was designed to be larger than the volume of the briquette biomass that will be burned within it. This ensures that there is adequate space for air circulation, which is essential for efficient combustion. The larger volume also allows for the expansion of gases during combustion, preventing excessive pressure build-up that could compromise the stove's structure or safety.

Results and discussion on the performance evaluation of the stove

The results of the performance evaluation conducted on the designed and fabricated biomass briquette-fired adjustable stove in the Nigerian Defence Academy Mechanical workshop are tabulated in Tables 2 to 4.

Plate 6: Experimental Set-up for Water Boiling Test

4.2 Water Boiling Test (WBT) Results

The water-boiling time responses using 2.5 kg of water, (from 33 °C to 102 °C), are shown in Tables 1 to 2. Boiling 1 kg of water would take 3.36 mins/kg and a specific fuel consumption of 0.294 kg/kg.

Table 2 Results for Boiling of Water

Parameters	Values	Units
The initial temperature of the water	33	^oC
The final temperature of the water	102	^oC
The weight of the empty pot	0.70	Kg
The initial weight of the fuel	0.75	Kg
The final weight of the fuel	0.60	Kg
The weight of the fuel used	0.15	Kg
The initial weight of the water	2.50	Kg
The final weight of the water	1.99	Kg
The weight of the water evaporated	0.51	Kg
Total time in boiling water	21	Mins

Table 3 Change in Temperature of the water at 5mins Intervals.

Time (mins)	Temperature (^oC)
0	33
5	41
10	52
15	84
20	93
25	102

Table 4 Values obtained from the tests carried out.

Parameter	Value	Unit
Efficiency	70.03	%
Burning rate	0.426	Kg/hr
Specific Fuel Consumption (S.F.C)	0.294	Kg/Kg
Time spent	8.4	Min/Kg
Value of heat utilized	4,830	KJ/Kg

The temperature change during the water boiling test at five-minute intervals (Table 3) was recorded, and key performance metrics for the briquette-fired adjustable stove were calculated under test scenario 4.1.2: stove efficiency (70.03%), burning rate (0.426 kg/h), specific fuel consumption (0.294 kg/kg), and time spent boiling (8.4 min/kg). Water began boiling at 21 minutes at 102°C, as shown in Plate 6.

The efficiency of 70.03% closely aligns with [14]'s reported 70.51% for a modular briquette stove but surpasses the 68% efficiency reported by [31] for coal briquettes and 46.11–44.29% for a modified stove by [32]. Variations may be attributed to differences in biomass moisture content, compressive pressure, and particle size.

The lower burning rate achieved reflects efficient fuel utilization, conserving resources and reducing emissions compared to solid wood fuel [33]. Specific fuel consumption (0.294 kg/kg) highlights fuel efficiency and pollutant reduction, outperforming traditional three-stone stoves and matching improved designs [34], [35].

Boiling times (8.4 minutes) align with similar studies [36]: 7.7–8.4 minutes; [37]: 12–20 minutes for gas and biomass stoves). The calorific potential of 4,830 kJ/kg and sensible heat transfer of 724.5 kJ confirm the briquettes' energy density and the stove's efficient energy conversion.

This biomass briquette-fired adjustable stove demonstrates competitive performance in efficiency, fuel use, and adaptability. The integration of an adjustable combustion chamber and effective insulation addresses gaps in prior designs, positioning it as a superior cooking solution.

V. CONCLUSION

The briquette-fired adjustable stove developed in this study demonstrates remarkable thermal efficiency, specific fuel consumption, and adaptability. Achieving a thermal efficiency of 70.03%, the stove aligns with or surpasses the efficiency reported in similar studies while significantly reducing fuel consumption and environmental emissions. The design prioritizes user convenience through features such as an adjustable combustion chamber and effective insulation, ensuring optimal heat transfer and fuel utilization.

Furthermore, the integration of locally sourced materials, such as groundnut shell biomass and cassava starch as binders, highlights the stove's cost-effectiveness and environmental sustainability. Adopting such stoves can contribute significantly to reducing reliance on traditional biomass fuels, promoting cleaner energy alternatives, and addressing public health and environmental challenges in rural and suburban regions. This project underscores the potential of innovative design and local resources to meet global energy needs sustainably.

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