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Air-Regulated Dual Stove for Domestic Cooking: Design and Development.

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ABSTRACT

The paucity and often unaffordability of clean energy for cooking in Nigeria has not only led to dwindling economic fortunes of citizens but has significantly impacted negatively on the standard of living of many households. With rising prices of electricity and Liquefied Petroleum Gas (LPG), the average Nigerian household is left with no option than to seek for reliable alternative to these two major sources of clean energy for domestic cooking. This informs the need for the design and development of an effective alternative in the form of a dual stove. In this work, the design and development of an efficient air-regulated dual (charcoal and wood) stove is presented as an alternative for rural and semi-urban households. The design was implemented using empirical correlation and solid works software. The development of the designed dual stove was carried out using standard workshop tools and machines such as center lathe machine, power drilling machine, rolling machine, bending machine, arch welding machine, cutting and grinding machine, steel and stainless steel electrodes. Design result show reactor/stove barrel external and internal diameters of 260mm and 264mm respectively, reactor height of 293mm, cook top diameter of 230mm, wood charging slot diameter of 85mm, grate diameter of 259mm, and top cover diameter of 262mm. The development of the air-regulated dual stove culminated into a prototype with unique features such as external ignition and quenching mechanism, sleeve for regulation of feed

air, efficient and compact combustion chamber and dual cabins for charging charcoal and fuel wood.

1.0 INTRODUCTION

The energy crises rocking the African continent particularly Nigeria has not only undermined the economic growth of the continent but has prevented over 200 million people from having sustainable and reliable clean energy. Access to Liquefied Petroleum Gas (LPG) or cooking gas and electricity has largely been denied for majority of Nigerian citizens. Liquefied Petroleum Gas which was increasingly becoming the major source of fuel for domestic use by households, schools, hotels and other related consumers in the Nigerian urban areas is no longer affordable. As at 2020 statistical data revealed that the consumption of LPG hit a record 1 million metric tonnes, however, in the rural areas it is estimated that less than 30% of the population use LPG as energy source while the remaining 40% use Kerosene and 30% use firewood owing to the high cost of cylinders, access to LPG etc (Ozoh *et al.*, 2018). The situation has long degenerated with soaring inflation, high exchange rate and dwindling earnings. In addition, the Nigeria power sector has witnessed a substantial decline in energy production, which forced many households and businesses to rely on the fossil fuel-based generators to meet the energy demand.

Currently, the available generation capacity is constantly hovering between 3,500MW and 5,000 MW while the demand is between 9, 051MW and 20, 00MW for a population of about 200 million people (Salau, 2020). More worrisome is the fact that about 80% of the Nigerian rural dwellers do not have access to electricity. This is an indication that there is a wide energy gap between the demand and supply of electricity (Okubanjo *et al.,* 2020).

In view of the above problems it is imperative to design and develop a cost-effective and efficient solution in the form of a dual (charcoal and wood) stove to ameliorate the problems.

Designing an efficient and cost effective dual (charcoal and wood) stove involves balancing several factors such as efficiency, safety, cost-effectiveness, environmental impact, adaptability and Accessibility: Dual stoves should be adaptable to the cooking traditions and preferences of the target users, as well as accessible in terms of affordability and availability of servicing/replacement parts. Designing an effective dual (charcoal and wood) stove also requires a multidisciplinary approach, incorporating principles of thermodynamics, combustion engineering and materials science.

Okino et al. (2021) assessed the thermal efficiency of an insulated fire stove using indigenous wood fuels used in rural Uganda (*Senna spectabilis*, *Pinus caribaea*, and *Eucalyptus grandis*). Computational fluid dynamics was used to simulate the temperature and velocity fields within the combustion chamber and for generating temperature contours of the stove. Obtained results indicated that *S. spectabilis* had the highest thermal efficiency of $35.5 \pm 2.5\%$, followed by *E. grandis* ($25.7 \pm 1.7\%$) and lastly *P. caribaea* ($19.0 \pm 1.2\%$) in the cold start phase when compared with traditional stoves.

Jani et al. (2020) designed a multipurpose cook stove mainly based on maximum utilization of waste heat in Traditional Cook Stoves. With the use of different methods and by applying some changes in design of Traditional Cook Stove; reduces smoke emissions, fuel consumption and time for cooking. It was observed that the improved design of Cook Stove fulfills different needs which cannot be possible in Traditional Cook Stoves. Due to complete combustion, the amount of fuel required is less than that of traditional cook stoves and reduces the pressure of deforestation. This Multi-Purpose Cook Stove is designed for people in the rural areas and for small food stall holders and it is beneficial to the environment as well as beneficial to society.

Ghadge (2020) developed a dual-purpose cook stove suitable for family size. The study revealed that the average thermal efficiency for dual purpose cook stove was found as 14.81 percent and 18.28 percent for babul sticks and neem sticks respectively and the power output ratings for dual purpose cook stove were found to be 1.56 kW and 1.69kW respectively with babul sticks and neem sticks. Specific fuel consumption (SFC) was found to be 0.326 and 0.297 for babul sticks and neem sticks respectively because of higher calorific value of babul sticks and neem sticks respectively i.e. 3796.8 kcal/kg and 3435.2 kcal/kg. Mixture of fine and coarse sand was used as insulation for cook stove. In water heating, the temperature rise per unit length was 120C/m and temperature rise per unit time was120 C/min.

Qing et al., (2016) in their study compared the thermal efficiency (TE) and emissions from solid fuel combustion in a newly developed under-fire heating stove and a typical traditional over-fire heating stove. The average TEs for burning all tested fuel types (semi-coke, anthracite, briquette, bituminous, lignite, and biomass) were 83 and 42% for the new stove and the traditional stove, respectively. The new stove was effective in reducing CO_2 and pollutant emissions per unit energy delivered to a radiator. The average reductions were ~50% for CO_2, 79% for $PM_{2.5}$, 95% for EC, 85% for benzo[*a*]pyrene equivalent carcinogenic potency, and 66% for eight selected toxic elements (Pb, Cu, Sb, Cd, As, Ag, Se, and Ni) in $PM_{2.5}$. It was observed in the study that improvements in stove technology are demonstrated as a practical approach for improving TE and reducing emissions of hazardous pollutants and CO_2.

Gujba et al. (2015) studied life cycle environmental impacts and costs of the household cooking sector in Nigeria from 2003 to 2030. Five scenarios were considered: business as usual, dominated by fuel wood stoves; low penetration of improved fuel wood and solar stoves, as planned by the government; high penetration of these stoves; increased use of fossil fuel stoves; and increased use of electric stoves. It was opined that if business as usual (BAU) continued, the environmental impacts would increase by up to four times and costs by up to five times, mainly because of high fuel wood consumption. Implementing the government's plan to introduce improved fuel wood and solar stoves would yield no environmental advantages, as the proposed number of stoves is too low. A higher number of the advanced stoves would lead to significant improvements in some impacts but would worsen others so that some trade-offs are needed. From the economic perspective, the scenario with a high use of advanced stoves had the lowest total costs but its capital costs are three times higher than for BAU. It was recommended that the government should prioritise the introduction of advanced stoves to reduce health impact from indoor pollution and reduce pressures on biomass resources; however, this may require subsidies. Fossil fuel and electric stoves would also help to preserve biomass and reduce health impacts from indoor pollution but would lead to an increase in greenhouse gas emissions and depletion of fossil resources.
Rasoulkhani et al. (2018) evaluated a top lit updraft biomass stove specifically modified to burn apple pruning waste. Additionally, the improved biomass cooking stove (ICS) was technically compared with traditional cook stove (TCS) based on Water Boiling Test and time to boil (TTB) instruction. Water and flame temperature variations were compared with a natural gas stove (GS), as the most common cooking device in Iran. It was observed that the average TTB was 12, 13, and 20 min for the GS, ICS, and TCS, respectively. The comparison of the regression equations indicated that the rate of increase in the flame and water temperature in both ICS and GS were similar. In general, better thermal efficiency was observed in the ICS (about 35 %) in comparison with the TCS (12.6 %). The specific and the total fuel consumption in the ICS were 73 and 67 % lower than that of the TCS, respectively.
Adegbola et al. (2021) designed, constructed and evaluated the performance of a dual powered cooker utilizing gas and electricity. It was concluded that the gas cooker component of the dual stove had higher overall thermal efficiency of 57% compared to the efficiency of 39 % recorded for the electrical component of the dual stove.
From all the literature reviewed and to the best of our knowledge, no design took into consideration the unique air regulation system in this design and external startup/quenching of the dual stove charcoal section, making this design and development a unique one and worth the research.

2.0 MATERIALS AND METHOD

2.1 Materials

Materials for dual stove design and development are specified and selected on their merit of durability, ability to withstand high temperature, frequent use, cost-effectiveness and local availability. The materials specified and used in the design and development of the dual stove include;

a. Mild steel plate – 3mm thick
b. Stainless steel flat bar
c. Steel mesh with 100mm holes
d. Steel plate for insert holder 5mm thick
e. Steel plate for ash tray 5mm
f. Handles
g. Hinges
h. Cutting discs – 2
i. Grinding disc – 2
j. Stainless steel electrodes
k. Mild steel electrodes

2.2 Machines and Processes

a. Marking out
b. Drilling of plate – Drilling machine – 5mm drill bit
c. Rolling of plate into cylindrical barrel with rolling machine
d. Welding of rolled seam
e. Rolling of stainless steel bar for cook top
f. Welding of stainless steel cook top seam with stainless steel electrode
g. Machining of insert slot(center lathe)
h. Chamfering of insert holder to fit reactor barrel (center lathe machine)
i. Machining of top cover (center lathe)
j. Slotting of top cover to accommodate cook top. (center lathe machine)
k. Welding of stainless steel cook top
l. Cutting off the reactor barrel to create wood charging opening
m. Welding of:
    i. Insert holder
    ii. Ash tray (removable)
    iii. Base
    iv. Grate
    v. Hinges
    vi. Handles
    vii. Mesh for wood charging
n. Vice for gripping
o. Grinding of;
    i. Cook top
    ii. Reactor barrel
    iii. Grate
    iv. Insert
    v. Other components
p. Finishing
q. Painting
r. Design – Procedure
s. Solid works
t. Solid works

2.3 The Design

In the design of this environmentally friendly and efficient stove, certain design considerations were taken into account which includes:

a. Cook top material: The cook top material made of stainless steel flat bar was selected to prevent pitting corrosion.
b. Fire box type: This was designed to maximize heat transfer from the stove to the cook surface
c. Air intake: The air intake was designed to regulate the combustion process. Intake vents were designed to allow oxygen into the combustion chamber and exhaust vents to release by-products of combustion.
d. Material selection: All materials were selected on their merit of durability, ability to withstand high temperature, frequent use, cost-effectiveness and local availability.
e. Detailed design: Detailed drawings were made using solid works software to specify each component.

f. Dimension: Proper sizing of stove components and dimensions were done. The dual stove components dimensions were based on conventional/traditional stove dimensions with tradeoffs to improve thermal/combustion efficiency.
g. Fire proof base: The base was made of mild steal to act as fire proof.
h. Combustion chamber: The combustion chamber was designed for efficient combustion and effective heat transfer to the cooking surface.
i. Ash tray: Ash tray was designed in a removable form for ease of removal.
j. Grate: The grate was designed to support the wood and to allow ash to be collected at the tray.

These design considerations were critically analysed and the analysis formed the bases for the design of the individual components of the dual stove.

2.3.1 Design Equations

Some empirical equations used in the design of the dual stove include the famous Fourier's Law equation for heat conduction, given by;

$$Q_{cond} = -\frac{k_t A \Delta T}{\Delta x} = \frac{k_t A(T_{hot} - T_{cold})}{(x_{cold} - x_{hot})} \quad (1)$$

Where:

k_t = thermal conductivity of the material (W/mK)
ΔT = temperature difference between the metal surface
Δx = thickness of the plate or wall (m)
A= cross-sectional area perpendicular to the direction of heat transfer

Convective heat transfer also takes place during the use of the stove hence convective heat transfer is given by;

$$Q_{conv} = hA(T_\infty - T_s) \quad (2)$$

Where:

T_∞ = bulk temperature of the surrounding fluid
T_∞ = surface temperature of the container
h = convective heat transfer coefficient in (W/m^2K)
A = surface area of the heated container

The quantity of heat required to cook a given mass of food is given by;

$$Q = m * C * (T - T_0) \tag{3}$$

Where:

T = average cooking temperature
m = mass of a cooking medium (1 kg | 1ltr)
C = specific heat capacity of the fluid (4.168 kJ/kgK)
T_0 = initial fluid temperature

The stove thermal efficiency is derived from the following equation;

$$\eta = 100 \times \frac{(m_w C_w + m_p C_p)}{m_f \times CV} \times (Tw_2 - Tw_1) \tag{4}$$

$$\eta = \frac{E_{out}}{E_{in}} = \frac{m_f C_f \Delta T_f}{IV \Delta t} \tag{5}$$

Where:

P = the cooking power
η = thermal efficiency of a cooker (%)
m_w= mass of cooking fluid (1 kg)
m_p= mass of cooking pot with lid (kg)
CV = calorific value (45780 kJ/kg)
I = current flowing through the coil (9 A)
V = electric potential difference (220 v)
C_p=specific heat of CO_2 gas at constant pressure (0.8956 kJ/kgK)
C_f = specific heat capacity of cooking fluid (4.168 kJ/kgK)
G = maximum heat intensity of the burner surface (W/m^2)
ΔT_f= difference between the final and initial water temperature.
Δt = period of time required to achieve the desired temperature

2.3.2 Design of Components

Based on the design considerations, the design requirements and constraints were defined and an initial concept generated based on the requirements. Solid works software was used to setup the design window. The component dimensions were specified using the dimensions of existing dual stoves as: reactor/stove barrel external and internal diameters of 260mm and 264mm respectively, reactor height of 293mm, cook top diameter of 230mm, wood charging slot diameter of 85mm, grate diameter of 259mm, and top cover diameter of 262mm. The various parts of the stove were modeled and assembled using solid works software. In the software, the design was refined by exploring different configurations after considering factors such as size, shape, heating capacity and user – interface. The most promising and suitable concept was chosen and developed using the design specifications. A 3-D model was developed with the aid of 2-D sketches using solid the software.

2.4 Development of the Designed Dual Stove

The 3mm steel sheet was marked out and 5mm holes drilled using a motorized drilling machine. The 5mm mild steel sheet was equally marked and 10mm holes drilled on it to act as grate/ ignition/external quenching mecha-

nism.
The 3mm steel sheet was rolled in a rolling machine to form a cylindrical barrel which formed the combustion chamber/reactor/stove. The barrel seam was welded to form a reactor. A portion of the rolled cylindrical barrel was cut and recessed to form the insert. The insert is also used to regulate the amount of air into the stove from where part of the title 'air-regulated' was derived. It also functions as a control mechanism for flame from the firewood.
The 5mm drilled holes formed the air vent for the control/regulation of air to the stove. The stainless steel flat bar was also rolled in the rolling machine. The seam was welded using stainless steel electrodes. The rolled stainless steel flat bar was crafted to form the stainless steel cook top. Part of the crafting included creation of slots on flat bar pieces to form the cook top stand which was weld to the circular cook top. The universal lathe machine was used to machine the grate/ignition/external quenching plate to fit into the stove barrel/reactor.
The lathe machine was equally used to form a groove on the machined top cover for the removable stainless steel cook top to sit.
The grate holder was welded on the stove barrel to hold the grate in place. The grate holder was also grooved to house the steel insert. The insert regulates the amount of air into the stove and allows flame from the wood portion of the dual stove to be directed to the cook top.
Three circular holes were cut on the stove barrel body to create positions for wood slots, the holes were grinded. Two of the cut pieces were hinged to form covers the holes. Only one of the holes was left open. The holes with covers acts as air – regulators to either increase burning rate and consequently wood consumption or reduce burning rate and consequently the amount of wood consumed as the case may be.
Another portion of the stove barrel close to the base was opened halfway to create the ash tray. Above the ash tray a 10mm steel mesh was welded to form the base for wood charging/loading. Two handles were welded to the body of the stove for carriage. A handle was also welded each to the ash tray and removable grate/ignition/external quenching mechanism. Hinges were also welded to the top cover and the stove body to enable the stove to be easily dismantled.
Grinding operation was carried out to ensure proper finishing of the stove assembly. Body filler was applied to ensure good finish. The stove was then painted. The stove assembly comprising all the parts is shown in the result and discussion section.

3.0 RESULTS AND DISCUSSION

3.1 Design Results

The dual stove assembly solid works workbench is shown in figures 1 to 3. The workbench comprises of command features such as the layout, sketch, markup, evaluate, blocks, add-ins and flow simulation. These features were skillfully managed and manipulated to produce the stove design shown in figures 4 to 13.

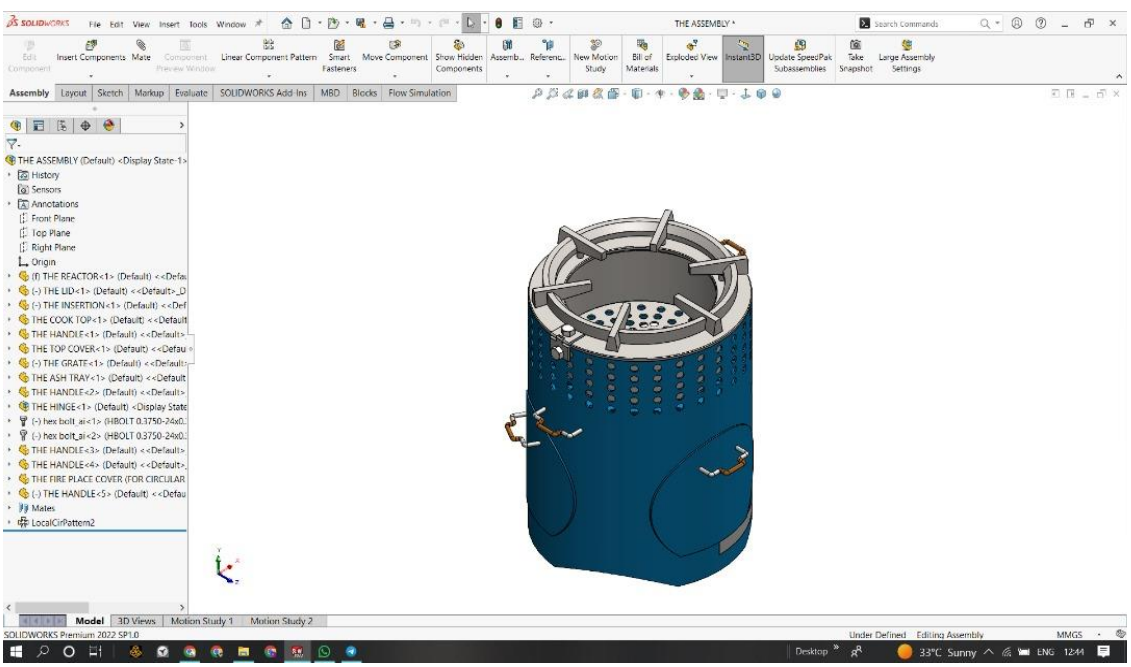


Figure1. Solid works workbench A

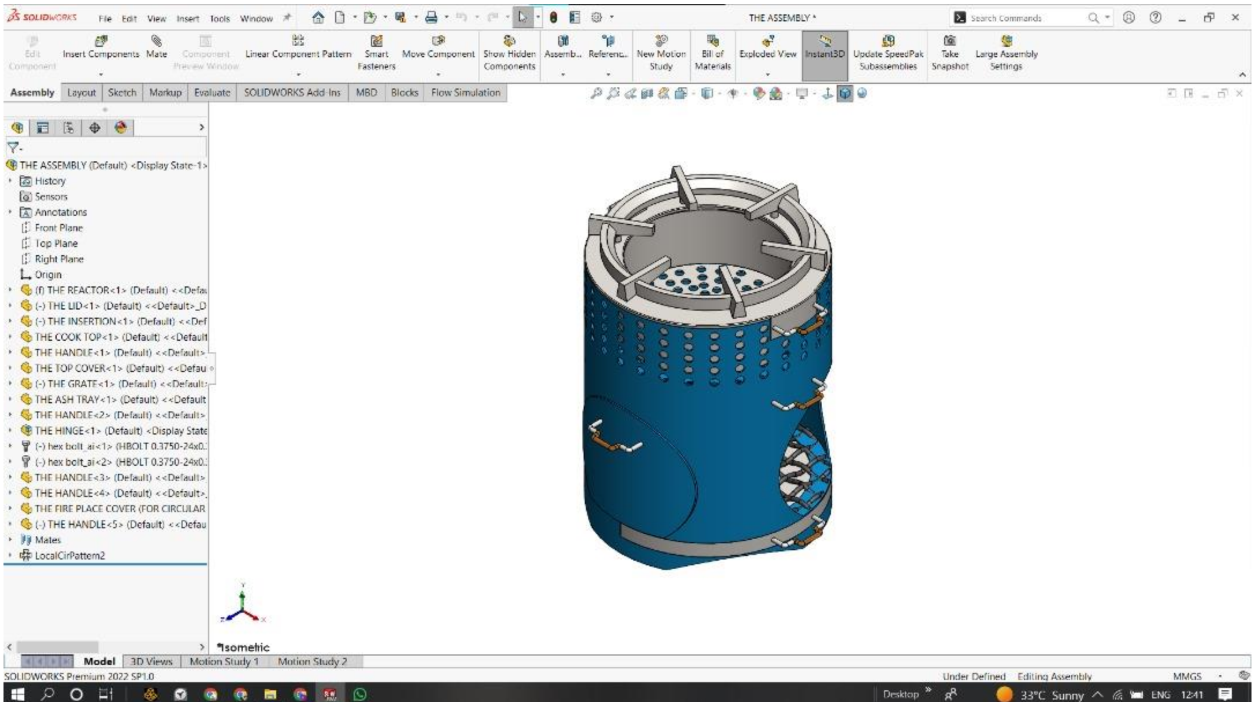


Figure 2. Solid works workbench B

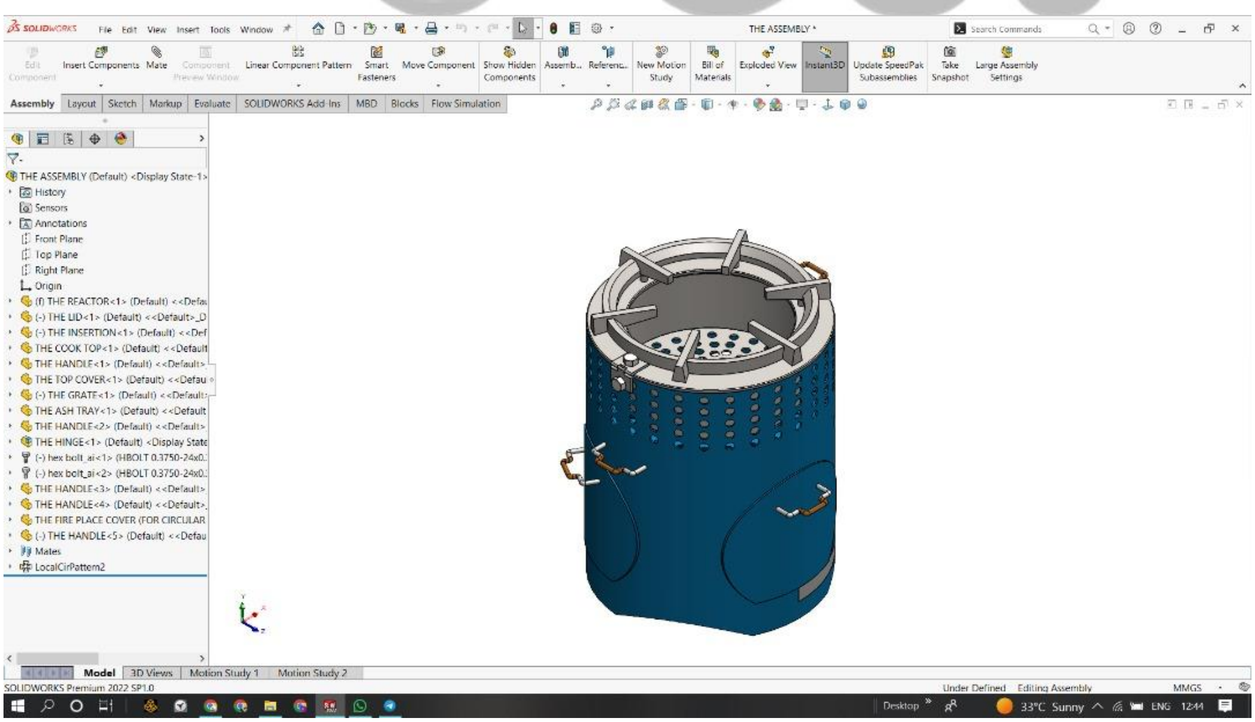


Figure 3. Solid works workbench C.

Figure 4 shows the exploded diagram of components of the designed stove. The components include the cooktop, top cover, sleeve, grate, mesh, stove barrel, hinges, handles and the ash tray.

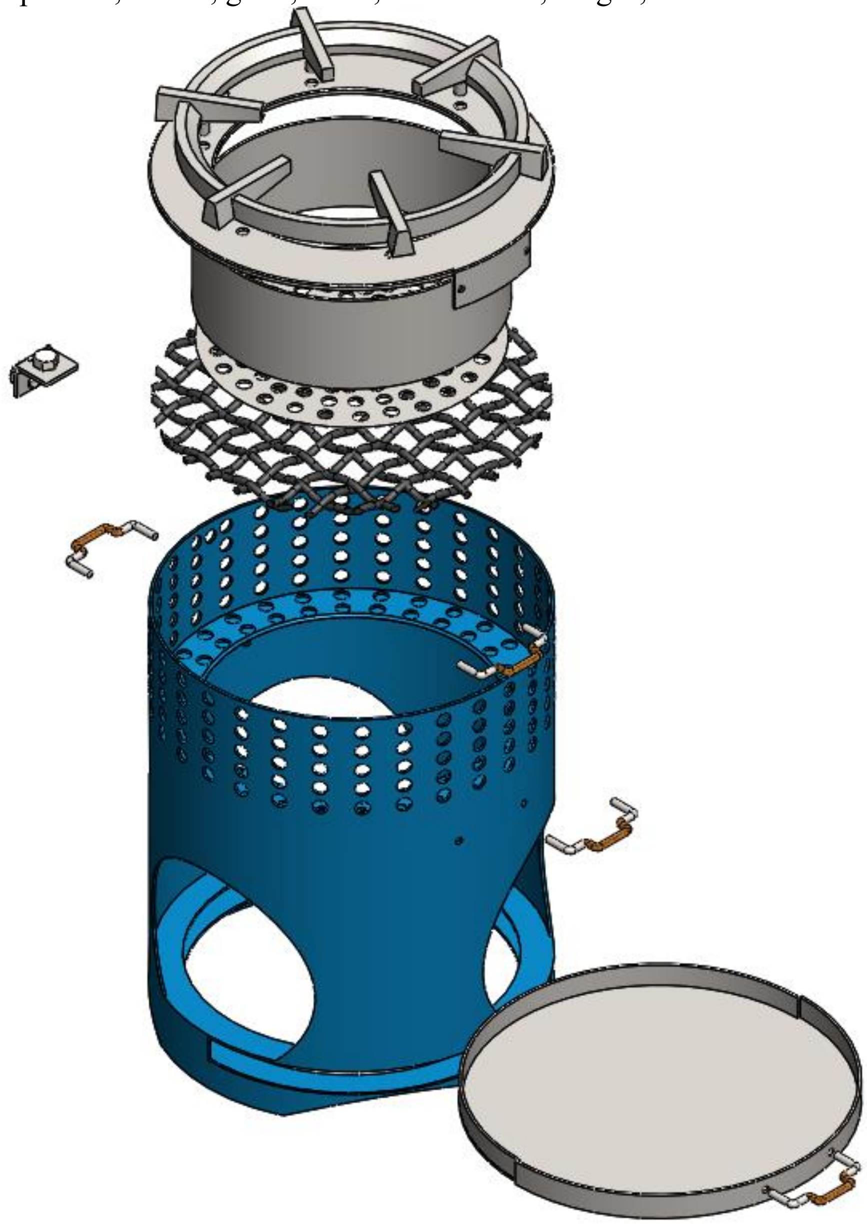


Figure 4. Exploded view of dual stove

Figure 5 shows the front view of the designed stove. Visible components include the cooktop, stove barrel, handles, wood charging slot and the ash tray.

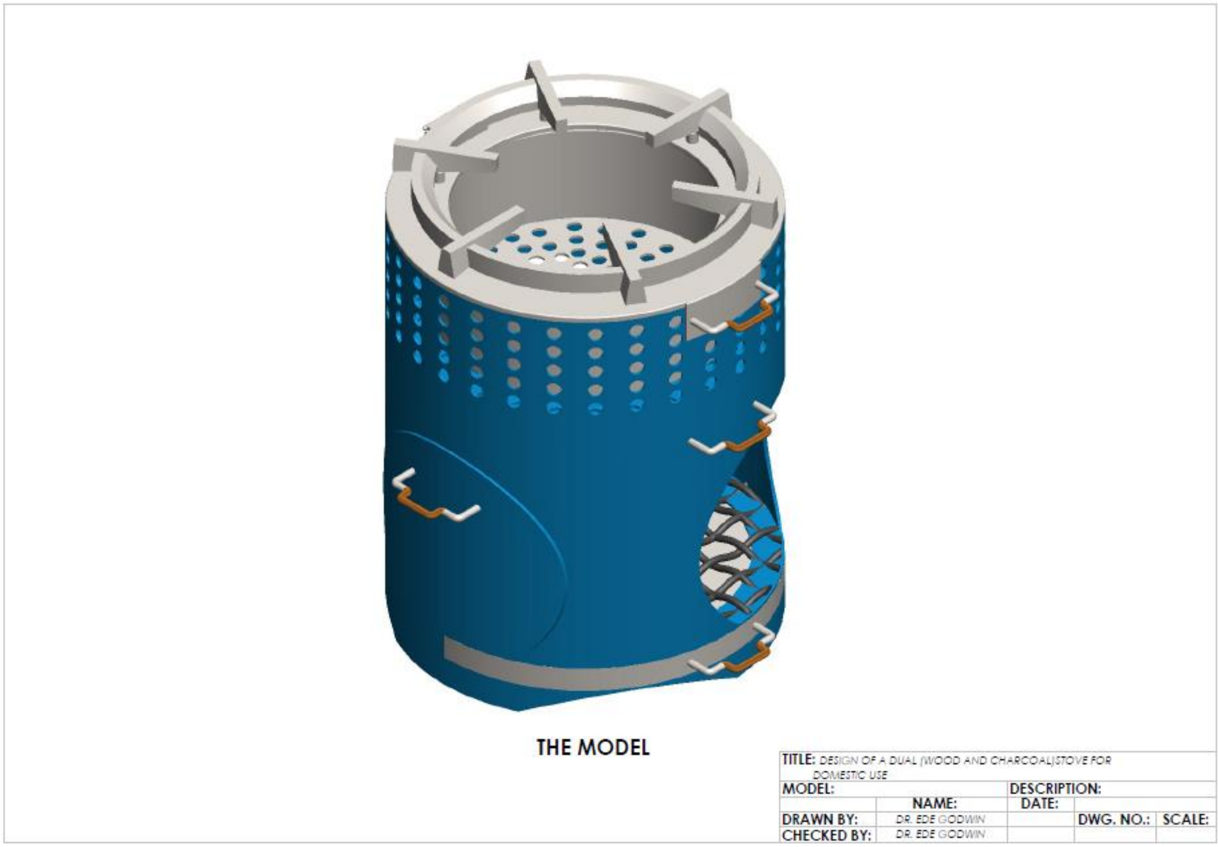


Figure 5. Front view of dual stove

Figure 6 shows the top view, isometric view, front view and end view of the designed stove.

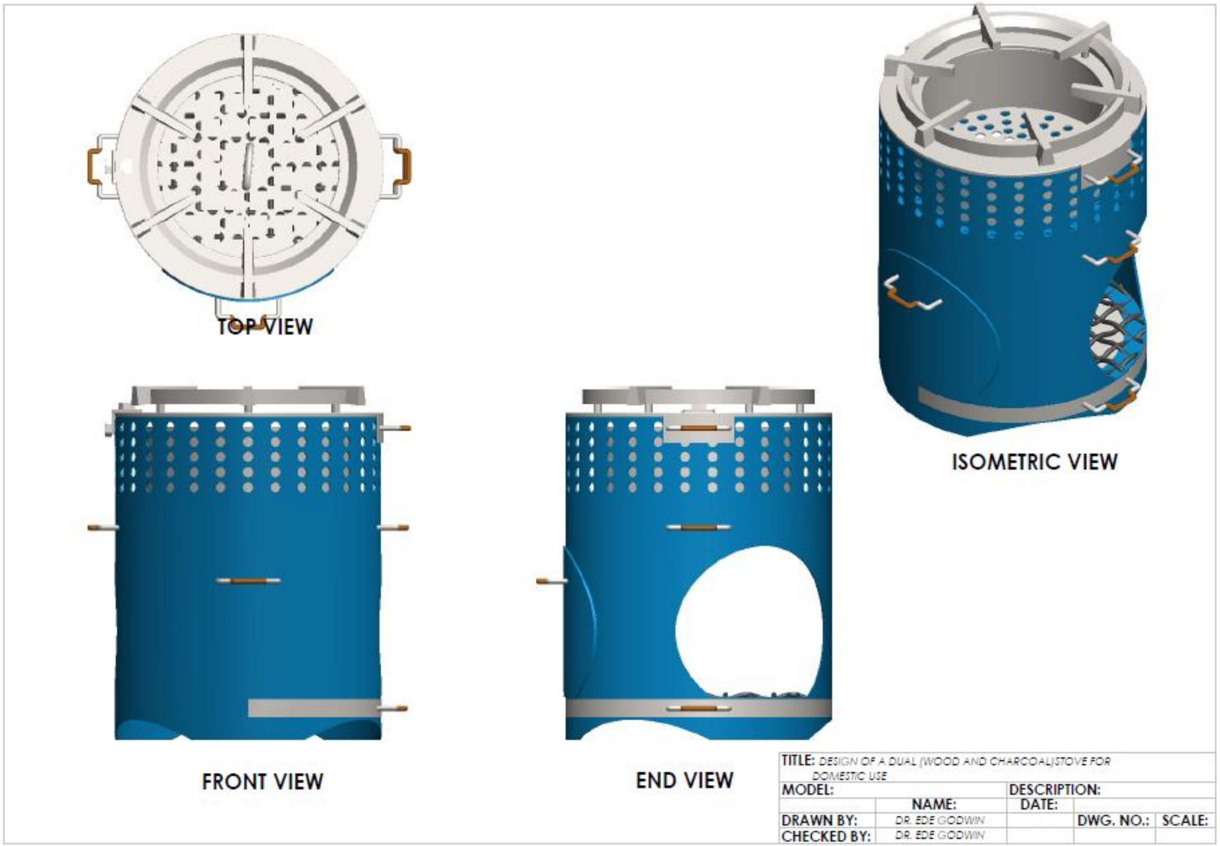
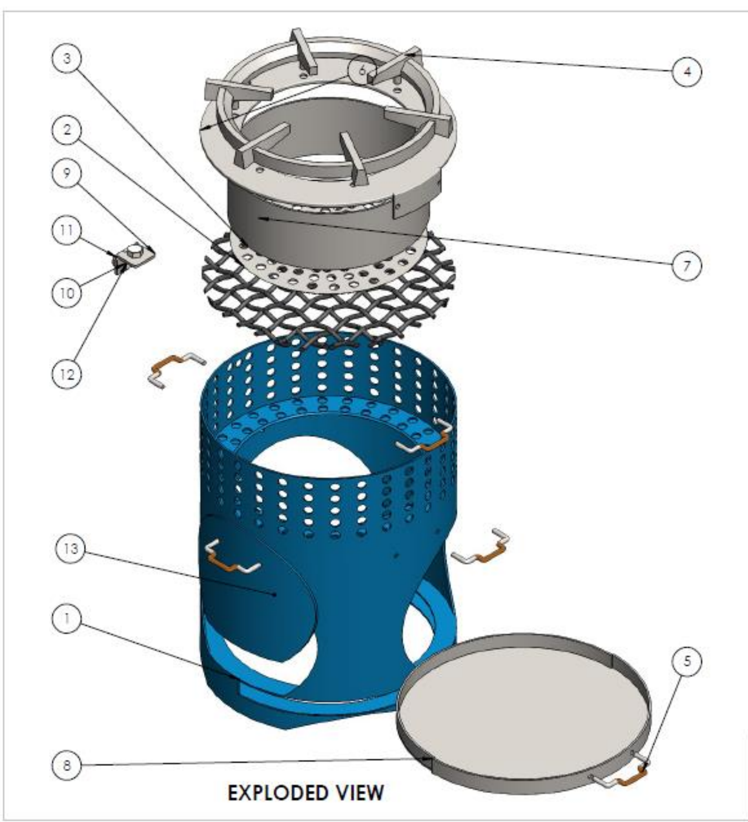


Figure 6. Different views of dual stove

Figure 7 shows the exploded view with bill of materials for the designed stove.



ITEM NO.	PART NUMBER	QTY.
1	THE REACTOR	1
2	THE LID	1
3	THE INSERTION	1
4	THE COOK TOP	1
5	THE HANDLE	7
6	THE TOP COVER	1
7	THE GRATE	1
8	THE ASH TRAY	1
9	PART 1	1
10	PART 2	1
11	PART 3	1
12	HBOLT 0.3750-24X0.375X0.375-N	2
13	THE FIRE PLACE COVER (FOR CIRCULAR FIRE COVER)	3

BILL OF MATERIALS

Figure 7. Exploded view of dual stove with bill of materials

Figure 8 shows the engineering drawing with dimensions of the ash tray, insert, cook top and the handles.

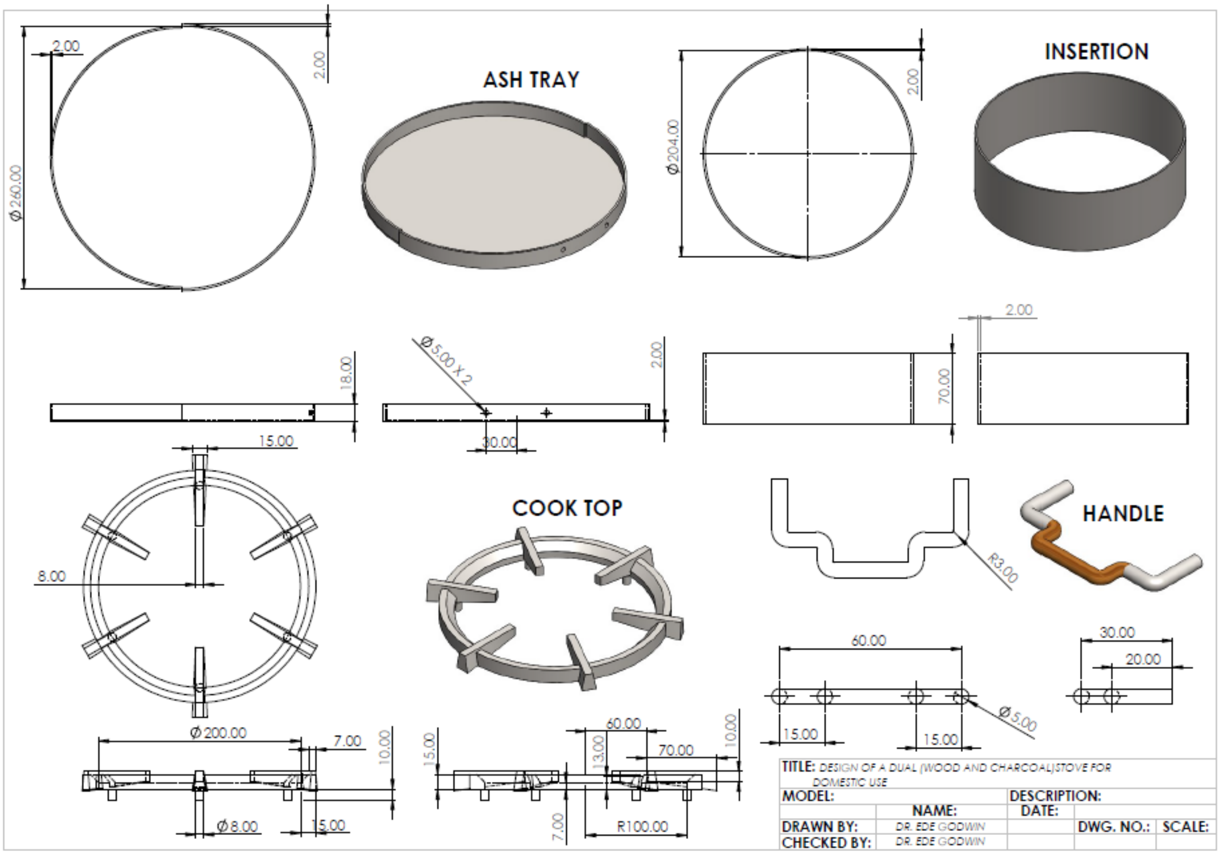


Figure 8. Components of dual stove

Figure 9 shows the engineering drawing of the stove reactor/barrel with dimensions of the wood charging slot, barrel diameter and height.

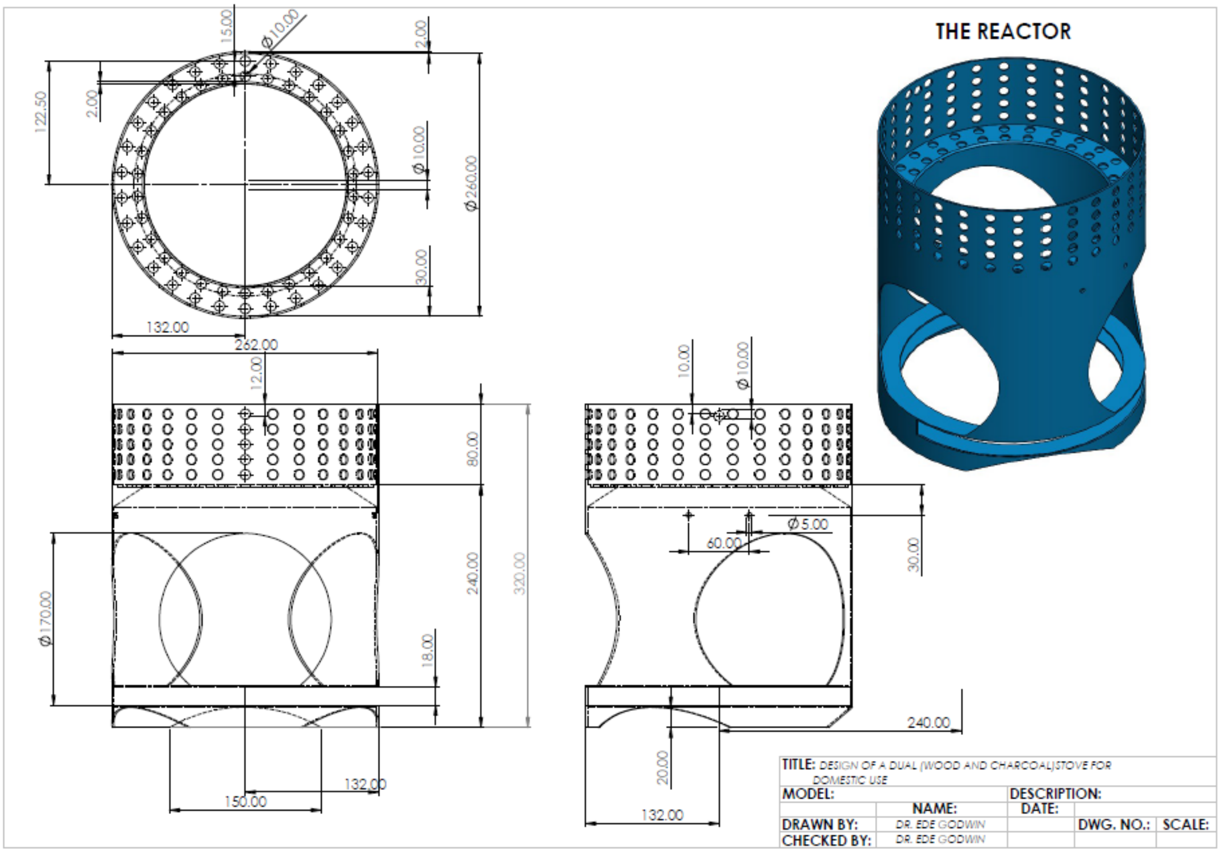


Figure 9. Components of dual stove

Figure 10 shows the engineering drawing of the top cover and lid with dimensions.

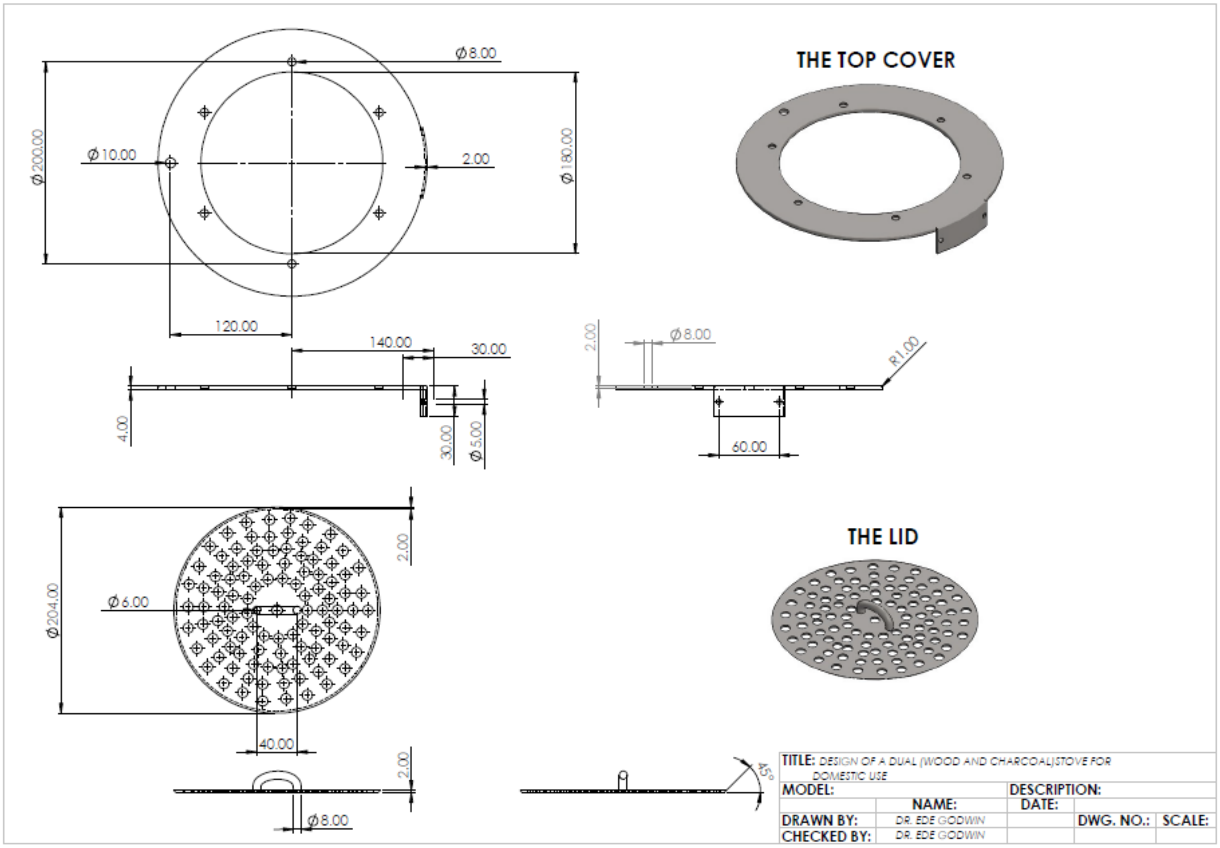


Figure10 Components of dual stove

Figure11 shows the engineering drawing of the grate with dimensions.

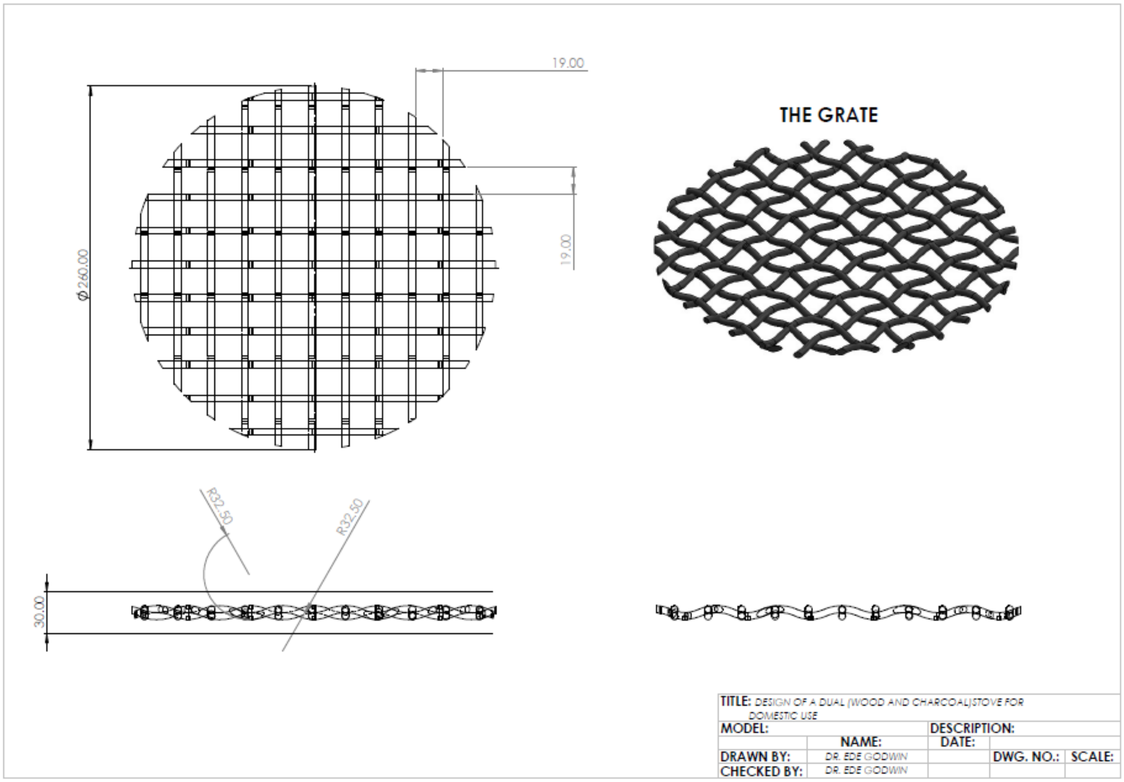


Figure11. Components of dual stove

Figure 12 shows the engineering drawing of the hinges with dimensions

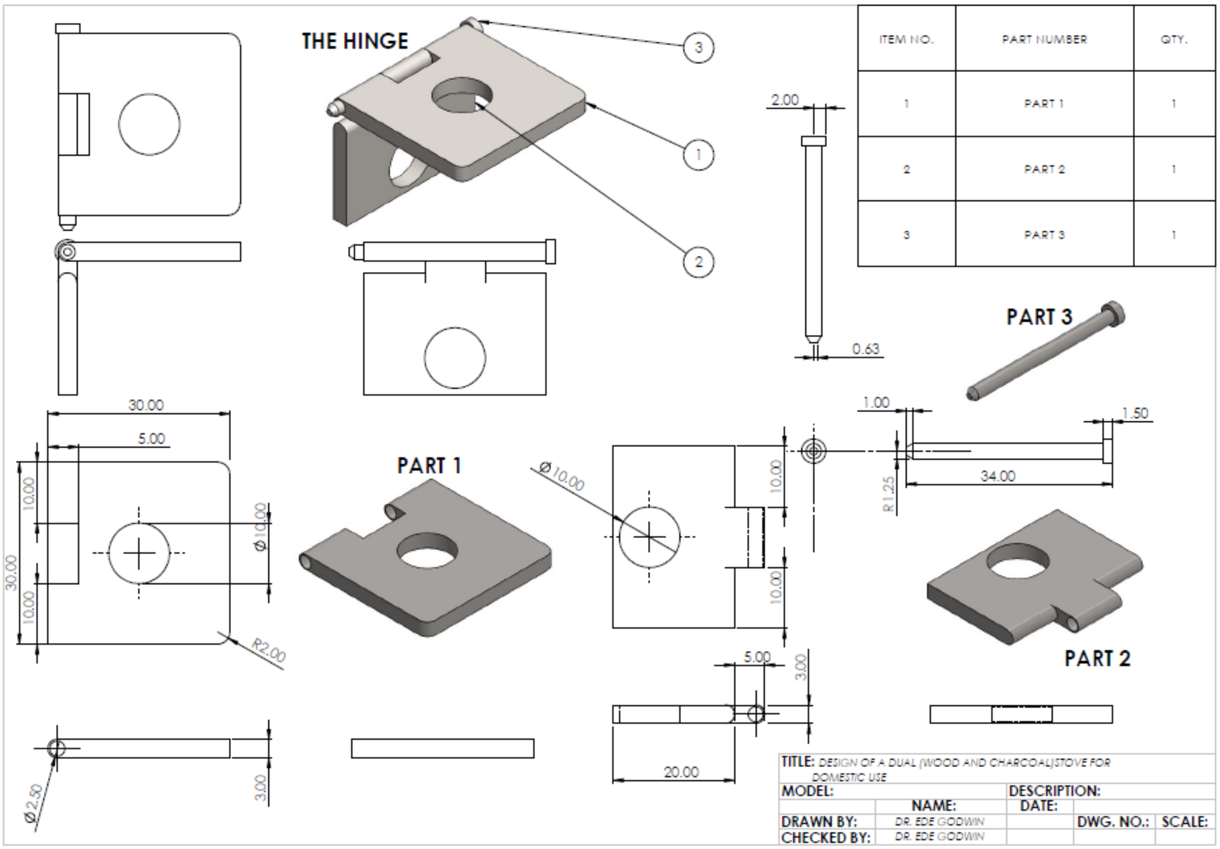


Figure12 Components of dual stove

Figure 13 shows the engineering drawing of the wood slot cover with dimensions.

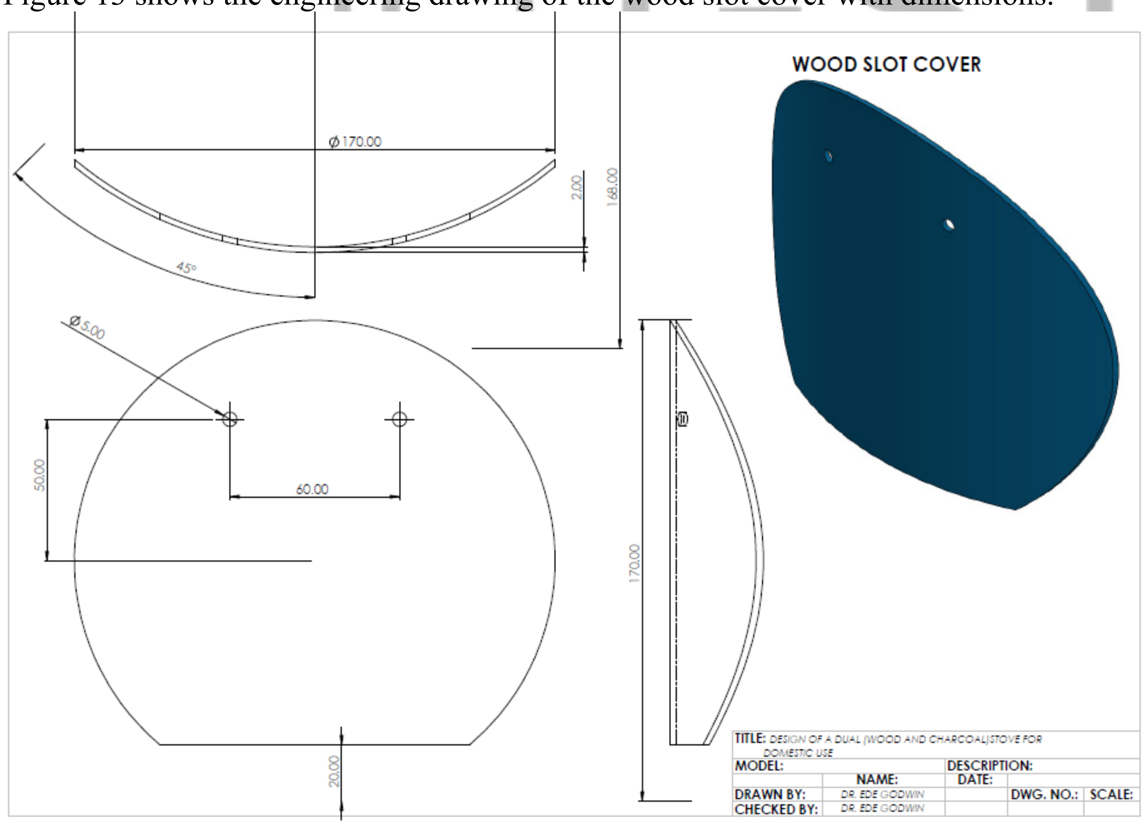


Figure13. Components of dual stove

3.2 Development Results

Figure 14 shows cutting and grinding operations on the stove assembly.

Figure14 Fabrication of dual stove components

Figure 15 shows lathe machine machining stove components

Figure15. Fabrication of dual stove components

Figure 16 is the pictorial view of the developed dual stove.

Figure16. Fabricated dual stove

3.3 Dual stove parts and their functions

In no particular order, the components/parts of the dual stove and their functions are:

a. Stainless steel cook top: The stainless steel cook top holds or acts as stand for the cooking pot. The cooking pot rests on it during application of the stove.
b. Grooved Top Cover: The circular grooved top cover acts as support for the cook-top. The cook-top sits on the circular grooved cook top. It is hinged to allow for opening/closing charcoal portion of the stove.
c. Cylindrical insert: the cylindrical insert acts as an air – regulator for the charcoal portions of the dual stove. It also directs flame from the wood portion of the dual stove to the cook top for maximum efficiency.
d. Grate: The 10mm holed grate acts as base for loading of charcoal. It is made removable to allow for external quenching and ignition of the stove after cooking. The 10mm holes drilled concentrically allows ash to freely drop during use of the stove.
e. Grate/insert holder: The function of the cylindrical and grooved grate/insert holder is to hold in place the grate and the insert. It is a grooved ring welded to the body of the dual stove.
f. Covered circular holes: The covered circular holes functions as the charging inlet and outlet for the wood portion of the stove. They also allowed flow of air in and out of the dual stove.
g. Handles: The handles are used to carry the dual stove and for opening of the top cover, grate and ash tray.
h. Circular mesh: The circular mesh supports the loading of firewood on the dual stove.
i. Removable ash tray: The removable ash tray collects the ash that falls from the grate and mesh for disposal.
j. Base cover: The base cover support the ash tray and prevents littering of remnant ash. It also contributes to the aesthetic beauty of the stove assembly.
k. The base. The base is made of folded 3mm sheet metal. It supports the entire dual stove assembly.

CONCLUSSION

This work focused on the design and development of an air regulated dual stove for domestic cooking. The design was implemented using empirical correlation and solid works software. The development of the designed dual stove was carried out using standard workshop tools and machines such as center lathe machine, power drilling machine, rolling machine, bending machine, arch welding machine, cutting and grinding machine, steel and stainless steel electrodes. Design result show reactor/stove barrel external and internal diameters of 260mm and 264mm respectively, reactor height of 293mm, cook top diameter of 230mm, wood charging slot diameter of 85mm, grate diameter of 259mm, and top cover diameter of 262mm. The development of the air-regulated dual stove culminated into a prototype with unique features such as external ignition and quenching mechanism, sleeve for regulation of feed air, efficient and compact combustion chamber and dual cabins for charging coal and fuel wood.

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