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Design and Fabrication of an Oil Fired Lift – Out Cast Iron Crucible Furnace using Locally available Materials

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Abstract: The research work presents the design concept and production of a portable Bale-out cast iron crucible furnace that is fired with diesel fuel. Therefore, the work deals with the design, production and testing of oil fired crucible furnace using locally sourced materials. The components of the oil fired crucible furnace are; furnace drum, crucible pot, brick lining, plinth, furnace cover, furnace cover opening and closing mechanism, blower, hose, air valve, burner nozzle, diesel valve, diesel tank and tank stand. Design drawings were produced and mild steel sheet was used for the production of the furnace, while the other components needed for the design were selected based on functionality, durability, cost and local availability. Tests were performed to evaluate the performance of the furnace. The results showed that it took the furnace 15.67mins to completely melt 5kg of aluminum scrap at 651.67^{o}C with 0.93 litres of diesel and it took 73.33mins to completely melt 5kg of scrap cast iron at 1209.33^{o}C with 3.93 litres of diesel. The furnace overall cost of production is one hundred and ninety thousand seven hundred naira only (₦190,700.00) which is lower than the conventional furnace which cost two hundred and ten thousand naira only(₦210,000.00) and is suitable for both in the rural and urban areas. The furnace is environmental friendly without health hazard to the workers and can be moved from one place to another unlike the local one.

I. INTRODUCTION

A furnace is an essential equipment or device in which the chemical energy of a fuel or electrical energy is converted into heat that is then used to raise the temperatures of materials [1]. Furnaces operating at low temperatures are often called ovens depending on their purposes and there are other furnace used at higher temperatures for various materials and purposes [1].

Furnace is used for high temperature heating to melt metals for casting or heat materials to change their shape (eg, forging, rolling) or properties (heat treatment) [2]. Since exhaust gases from the fuel comes in contact with the surface of materials, then the type of fuel used is important because some materials will not tolerate sulphur in the fuel. Solid fuels generate particulate matter [2], which will interfere the material placed inside the furnace. For this reason [2], most furnaces use liquid fuel, gaseous fuel or electricity as energy input. Furnace ideally should heat as much of material as possible to a uniform temperature with the least possible fuel and labour. The key to efficient furnace operation lies in complete combustion of fuel with minimum excess air. On a general note, furnace is also employed in the heat treatment of metals in order to influence their mechanical and physical properties.

A crucible is a refractory container which can withstand temperature high enough to melt or otherwise alter its contents [3].

A crucible furnace is among the oldest and simplest furnaces used in the foundry; it is a piece of equipment used in foundry industry for melting metals for casting metallic wares such as machines, machine parts and other related engineering materials. It is mostly used in small foundries or for specialty alloy lines. The crucible or refractory container is heated in a furnace, typically fired with natural gas or liquid propane, although coke, charcoal, oil, or electricity can be used [4].

A cast iron crucible furnace is therefore one meant for melting and casting of cast-iron products [4]. The importance of the cast iron crucible furnace to the foundry industry as it affects the industrial and technological development of any nation cannot be overemphasized, since many machine components are made of cast iron.

The furnace is mounted on two pedestals above the floor level for planning the molten metal. Oil and air are admitted with pressure through a nozzle [4]. The crucible is placed in the heating chamber and is heated by the flames. The furnace can be stopped whenever needed and temperature can be controlled easily. This gives lesser pollution. However, improvements in efficiencies have been brought about by methods such as pre-heating of stock, preheating of combustor air and other waste heat recovery system [4]. Oil fired furnace mostly use furnace oil, especially for preheating and heat treatment of materials.

Therefore the aim of this work is to design and fabricate an oil fired bale-out cast iron crucible furnace using locally available materials that is portable, safe, economical and affordable to small and medium scale foundry shops.

II. MATERIALS AND METHODS

A. Description/Working Principle of the Furnace

Furnace design is a complex process, and the design can be optimized based on multiple factors. Furnaces in foundries can be any size, ranging from one to hundreds of tones capacities [5]. The furnace consists of an electric motor, blower unit, stand, and crucible furnace unit, the furnace also comprises a combustion chamber to which oil is fed and a crucible. Oil is fed to the combustion chamber through a hose and air is supplied by the blower.

The furnace is fired by igniting combustible materials such as wood in the combustible chamber. While the wood is still burning the valves that control the supply of diesel fuel on the diesel fuel supply pipe and air from the air blower through the nozzle respectively are slightly opened to allow in drops of fuel and air under pressure. The air is blown over the fuel to atomize as well as oxidize it for combustion. As the mixture of air and fuel blows over the pre-lit coal it helps to sustain the combustion. As this continues over time, the temperature rises gradually within and around the crucible pot, thereby melting its content.

When the crucible content is fully melted and is ready for pouring, the crucible is either lifted out by means of a lifting tong, which is usually handled by two persons depending on the size of the crucible pot and then poured into the prepared mould cavity or with the aid of a ladle, the molten metal is baled out and poured directly into the prepared mould cavity.

The designed crucible furnace assembly is shown in fig 1.

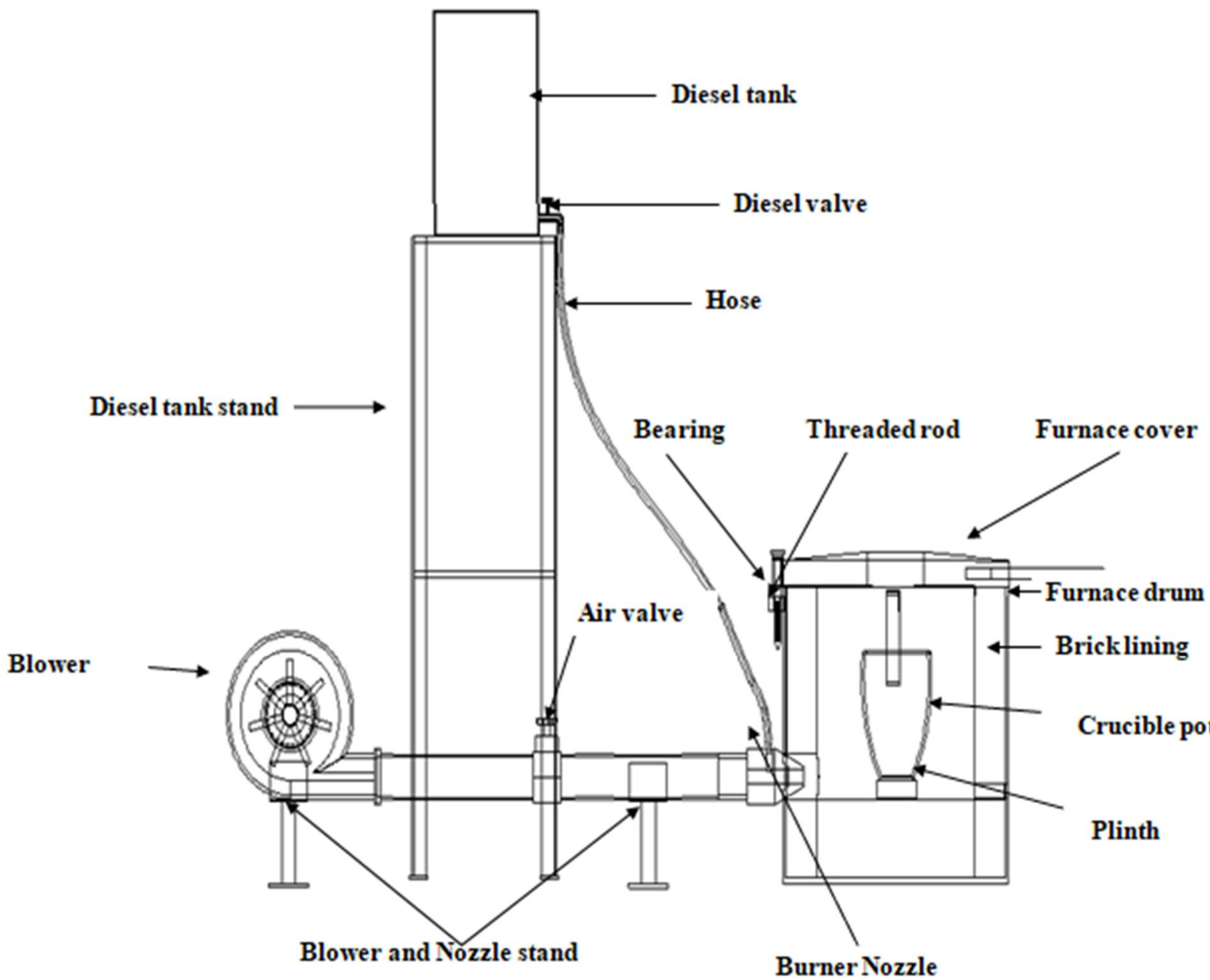

Fig 1: Drawing of the Cast-Iron crucible Furnace (side view wireframe)

B. Design Consideration

The following factors were considered in carrying out the design; production cost, type of fuel used (charcoal) and its availability, materials selection and their availability, flexibility in fabrication, ease of maintenance, durability, cost of the selected materials, availability of the tools and equipment for production, height and width of the furnace, blower and furnace capacity 20kg, and shape of the furnace.

C. Design Theory

The crucible furnace is a unit that operates under pressure at a very high temperature. The design of the furnace therefore, follows the criteria used for heat.

1) *Determination Of The Minimum Thickness Of The Furnace Walls:* The required thickness of the furnace wall to the design heat pressure is determined using the expression given by [5] as

$$t = \frac{pD_1}{2\sigma J - p} + C, \quad (1)$$

2) *Determination Of The Maximum Allowable Working Pressure For The Furnace:* Assuming the furnace is in new condition. The maximum allowable working pressure for the furnace is obtained using the expression [5].

$$p = \frac{\sigma jt}{R + 0.6t}, \quad (2)$$

3) *The Stresses Set Up In The Furnace:* Assuming uniform internal pressure, the stresses set up in the cylindrical furnace longitudinally are equal to half of the stresses set up circumferentially. The longitudinal pressure induces stresses on the metal seam circumferentially and the radial pressure induces stresses on the metal longitudinally.
4) *Determination Of The Thermal Stresses Set-Up In The Furnace Walls: Thermal* stresses are the stresses which result from restricting the natural expansion or contraction of the materials of the furnace wall due to temperature changes for the thin-walled furnace vessel, the longitudinal and circumferential thermal stress distribution over the thickness of the wall. Assuming a steady state condition is obtained from the expression suggested by [6] as;

$$\sigma t_{a=}\sigma l_a = \sigma C_a = \frac{-\alpha E(T_a - T_b)}{2(1-v)} = \frac{-\alpha E \Delta T}{2(1-V)} \; for\ the\ inside\ wall \quad (3)$$

and

$$\sigma t_{b=}\sigma I_b = \sigma C_b = \frac{\alpha E(T_a - T_b)}{2(1-v)} = \frac{\alpha E \Delta T}{2(1-V)} \; for\ the\ outside\ wall \quad (4)$$

5) *Investigation Of The Effect Of Internal Pressure On The Furnace Dimensions:* Hearn, [27] provides expressions that can be used to investigate the extent of dimensional changes due to the effects of internal pressure on the walls of the furnace
6) *The Change In Length Of The Furnace:* This can be determined from the expression. Change in length = longitudinal strain x original length

$$\text{Change in length } \Delta l = \frac{pd}{4tE}(1 - 2\gamma)l, \quad (5)$$

7) *Change In Diameter Of The Furnace:* Change in diameter due to the effect of the internal pressure in the furnace is obtained using this expression:

$$\text{Change in diameter } \Delta d = \frac{pd^2}{4tE}(2 - \gamma), \quad (6)$$

8) *Change in the Volume of the Crucible:* The expression for determination of the change of volume of the crucible is

$$\Delta v = \frac{pd(5 - 4\,\Upsilon)V}{4tE}, \quad (7)$$

but

$$V = \frac{\pi}{4}d^2 L, \quad (8)$$

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D. Design Calculation

Table 1: Design Calculations

Initial Data	Calculations	Results
J = 0.70 σ = 88x10^6N/m^2 d_1 = 0.80m c = 1.5x10^{-3}m assuming the working pressure is p = 7.5x10^5N/m^2 t =? where P is the design pressure from table, C is the corrosion allowance for the material, σ is the yield stress for the material, and J is the weld joint efficiency of the material	From equation 1 $$t = \frac{pd_1}{2\sigma j - p} + c$$ $$t = \frac{7.5\text{x}10^5\text{x}0.80}{2\text{x}88\text{x}10^6\text{x}0.70 - 7.5\text{x}10^5} + 1.5\text{x}10^{-3}$$ t = 0.00640m	The thickness of the furnace is 6mm
2.4.1 Calculation of maximum working pressure for the furnace (P)		
J = 0.70 σ = 88 X 10^6 N/m^2 R = 0.13m P = ? T = 3.0mm	Assuming the furnace is in new condition, from equation 2 $$p = \frac{\sigma j t}{R + 0.6t},$$ $$= \frac{88 \times 10^6 \times 0.70 \times 0.003}{0.13 + 0.6 \times 0.003}$$ $$= \frac{184{,}800}{0.1318}$$ $$p = 1{,}402{,}124\ N/m^2$$ $$p = 14.02 \times 10^5\ N/m^2$$	P = 14.02X10^5 N/m^2
2.4.2 Calculations of thermal stresses set up in the furnace wall (σt_a)		
$\alpha = 17 \times 10^{-6}\ m^2/s$ $E = 206 \times 10^9\ N/m^2$ $\upsilon = 0.3$ $t_a = 301k$ $t_b = 943k$ $\Delta t = 943 - 301$ $\Delta t = 642k$	From equation 3 $$\sigma t_{a=}\sigma l_a = \sigma C_a = \frac{-\alpha E(T_a - T_b)}{2(1-\upsilon)} = \frac{-\alpha E \Delta T}{2(1-\upsilon)}$$ The thermal streses set up inside the furnace wall Who's temperature is raise to 1380°C $$\sigma t_a = \frac{-\alpha E \Delta T}{2(1-\upsilon)}$$ $$\sigma t_a = \frac{-17.7 \times 10^{-6} \times 206 \times 10^9 \times 642}{2(1-0.3)}$$ $$\sigma t_a = \frac{-2.340 \times 10^9}{1.4}$$ $$\sigma t_a = -1.672 \times 10^9\ N/m^2$$	σt_a = -1.672X10^9 N/m^2 compressive

	From equation 4 $$\sigma t_{b=}\sigma l_b = \sigma C_b = \frac{\alpha E(T_a - T_b)}{2(1-\upsilon)} = \frac{\alpha E \Delta T}{2(1-\upsilon)}$$ The maximum thermal stress at the outside of the furnace wall is; $$\sigma t_b = \frac{2.340 \times 10^9}{1.4}$$ $$\sigma t_b = 1.672 \times 10^9\ N/m^2$$	$\sigma t_a = 1.672X10^9\ N/m^2$ Tensile The results shows that selected material is good for the furnace
The buildup of pressure within the furnace causes slight expansion of the furnace thus resulting in changes in the dimensions which are investigated below 2.4.3 Calculation of change in furnace dimension due to internal pressure		
P $=7.5x10^5 N/m^2$ t = 0.006 l_{fur} =0.85m v =0.3 d =0.80. E = $206x10^9 N/m^2$	Change in length of the furnace (*Δl) from equation 5* $$\text{Change in length } \Delta l = \frac{pd}{4tE}(1-2\nu)l$$ Change in length of the furnace wall (body) $$\Delta l = \frac{7.5x10^5x0.80x(1-0.6)x0.85}{4x0.006x206x10^9}$$ $\Delta l = 4.126x10^{-5}$m	Δl = $4.126X10^{-5}$m
P $=7.5x10^5 N/m^2$ t = 0.00 v =0.3 d =0.80. E = $206x10^9 N/m^2$	Change in diameter of the furnace (*Δd) from equation 6* $$\Delta d = \frac{pd^2}{4tE}(2-\nu)$$ The change in diameter due to the effect of the internal pressure in the furnace is $$\Delta d = \frac{pd^2}{4tE}(2-\nu)$$ $$\Delta d = \frac{7.5X10^5 X\, 0.8^2 X(2-0.3)}{4X0.006X206X10^9}$$	Δd = $1.650X10^{-4}$m

E. Construction

The designed furnace was constructed in the Mechanical engineering Department workshop of Ahmadu Bello University Zaria. The manufacturing process involved in the construction is fabrication work, cutting and welding. Different components were separately fabricated and later assembled. After assembling the sharp edges were chamfered and the structure was painted. The furnace consists of several components as presented in the working drawing, Appendix II. Therefore, the methods and steps adopted for this work are design theory, calculation and construction work, which involve numerous operations starting from material selection, measurement, cutting, folding, joining, etc up to the end of the work and testing of the furnace, the details for the fabrication process were given below.

1) *Construction Process:* Having selected the materials that meet the required specifications for the construction of crucible furnace, the fabrication processes and the equipment used are as tabulated below.

Table 2: Construction Process

S/N	Components	Materials	Fabrication process	Equipment/ tools used
1	Furnace drum	mild steel plate of 2.5mm thickness	-Folding the mild steel plate into a cylindrical shape of Ø610mm with the aid of a rolling /folding machine. - A circular mild steel plate of Ø 610mm was cut and subsequently welded to the bottom of the folded drum	Scriber, punch, steel rule, cutting disc and arc welding machine.
2	Furnace Lid	2.5mm mild steel plate	-The mild steel plate was cut and welded using gauge 12 electrodes. -The cover was impregnated/ filled with a refractory mixture - In order to firmly secure the insulating materials to the cover, pieces of rods were welded underneath the bottom part of the cover to hold the refractory mixture.	Scriber, punch, steel rule, cutting disc and arc welding machine.
3	Lining the Furnace Wall	Refractory bricks of 11mm (asbestos and clay)	-Refractory mixture comprising of fire clay and water as a binder to fill the spaces in between bricks in order for them to hold firmly together. -The base of the furnace was lined with a mixture of clay sand and water.	Hammer, grinding machine, and water.
4	Furnace cover	Mild steel sheet 3 mm thick.	-On a suitable location on a mild steel sheet mark Ø 422 mm draw a circle and cut it out - From the centre of the circular plate, draw a circle to circumscribe Ø220 mm hole - On a suitable location mark and cut out 1 piece 20 mm x 350 mm and 1 piece 20 mm x 450 mm - Attach (weld) the 2 metals at the ends of the circles respectively, to form a complete cover	Scriber, punch, steel rule, cutting disc and arc welding machine.
5	Burner Nozzle	mild steel cylindrical solid rod of length 300mm Ø120mm.	A tapered hole was bored through the cylindrical solid rod with the larger end having a diameter 120mm to serve as the inlet passage for air flowing from the air blower and the smaller end Ø20mm to serve as the outlet passage for the supply of air for combustion in the furnace.	Lathe machine
6	Diesel tank	mild steel plate of 2mm thickness	-Cylindrical shaped pieces with dimensions of 500mm by 3700mm were cut out of the mild steel plate with the aid of a cutting machine and thereafter welded together to form a cuboid-shaped structure with dimensions of 500mm x 370mm. - A hole of about 80mm diameter was bored at the base of the tank on one side and a pipe of about 12mm diameter was welded to it, to serve as fuel supply line to the furnace.	Scriber, punch, steel rule, cutting disc and arc welding machine.
7	The Plinth	Asbestos and clay	The plinth was made with bricks and fire clay as binder	Hammer, grinding machine, and water.
8	Crucible port	Mild steel 2 mm thick	-This is a port of Ø240 mm and length of 350 mm. - On a suitable location on a mild steel sheet mark a circle of Ø 310 mm and cut it out - From the centre of the circle, circumscribe Ø240 mm hole - Attach it to the crucible port at a distance of 40mm from the top	Scriber, punch, steel rule, cutting disc and arc welding machine.

F. Assembling of Parts

After all the parts were fabricated, the next step was coupling the furnace cover-opening/closing mechanism to the bearing. Thereafter, the furnace cover itself was then joined to the cover-opening/closing mechanism. The nozzle was at this point adapted to the furnace drum. The air blower which was bought already made was subsequently connected to the nozzle. Lastly the hose from the diesel fuel tank was linked to the furnace. See fig 2

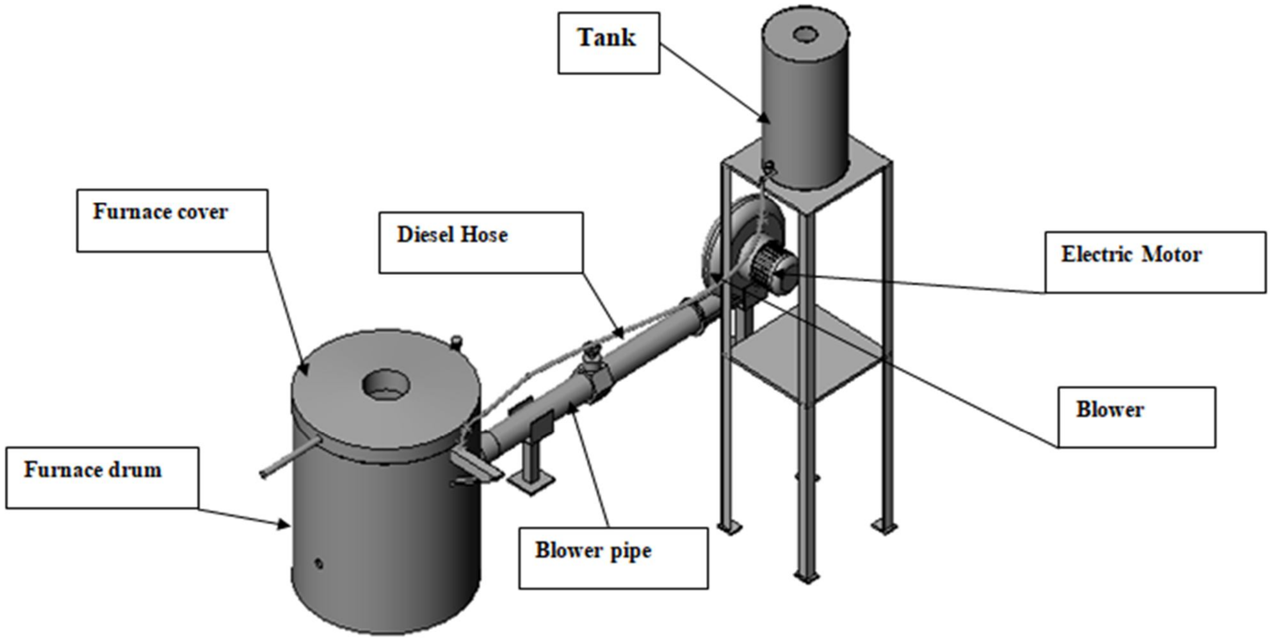

Fig. 2 Assembled Crucible Furnace

G. Performance Evaluation

1) *Measurement Of Temperature And Time:* The thermocouple and stop clock was used.
2) *Diesel Fuel:* The diesel fuel used for the work was obtained from within the research environment which was at NNPC filling station Mando Kaduna. About 50ltrs of diesel was obtained for this work.
3) *Cast Iron and Aluminum Scrap:* The cast iron and aluminum scrap used for the experiment was sourced from Panteka Market from the scrap sellers. About 20kg and 18kg of cast iron scrap aluminum scrap respectively were obtained.
4) *Testing:* The designed and fabricated crucible furnace along with accessories were assembled and stationed in the Department of Mechanical Engineering workshop furnace section, Nigerian Defence Academy Kaduna. The experiment was carried out in the workshop in order to reduce the effect of wind on operation.

a) Sequence of the testing Operation Procedures

The following steps were followed in testing the furnace;

i) Cast iron scrap was measured to get the exact 5kg.
ii) All the 5kg of scrap was further broken to small pieces and it was kept aside.
iii) Pour the diesel into the diesel tank.
iv) Light the charcoal fuel in the furnace combustion chamber.
v) Place the crucible inside the furnace.
vi) The scrap was feed in to the crucible.
vii) Open the diesel tank in order to allow diesel flow into the combustion chamber.
viii) On the blower to blow air into the combustion chamber to generate the required heat for melting of the cast iron.
ix) When the cast iron is completely melted, and reached its pouring point use approved tongs to fetch the molten metal from the crucible for casting.
x) Pour the molten metal into the sand or iron mould for the desired casting and allow it to solidify.
xi) End of the operation cycle.

5) *The Amount Of Fuel Used:* This was determined from the difference between the initial volume of the diesel before experiment and the final volume of diesel after the experiment.
6) *Cost Analysis:* Cost is an important aspect of engineering design and construction. The evaluation of cost of designed and produced crucible furnace has three components: material, labour and overhead costs. Material costs involve the detailed breakdown of materials and it sum up costs of all materials used. The labour cost is what was spent on labour during the manufacturing process, and overhead costs involve transportation and other miscellaneous expenses. Table 3.3 is a breakdown of the crucible furnace cost.

Table 3: Breakdown of crucible furnace cost

S/N	Description of items/materials	Unit	Qty	Rate(₦)	Amount(₦)
1.	2.5mm mild steel plate	Sheet	1	15000	15000
2.	3mm mild steel plate	Sheet	½	2000	10000
3.	20 inches out to out frange	Pieces	2	10000	20000
4.	3 inches pipe	Length	½	10000	5000
5.	3 inches ball valve	Piece	1	7000	7000
6.	½inches pipe	Length	¼	8000	2000
7.	½ inches valve	Pieces	2	1000	2000
8.	1inch angle iron	Length	½	6000	3000
9.	Air Blower	Piece	1	30000	30000
10.	Fuel Tank	Pieces	2	2000	4000
11.	Bolt and Nuts	Pieces	10	50	500
12.	20mm mild steel plate	Sheet	¼	28000	7000
13.	1½ inch mild steel pipe	Length	¼	4000	1000
14.	Bricks	Pieces	40	200	8000
15.	Fire clay	Bags	2	2500	5000
16.	½ inch hose	Yards	3	200	600
17.	Clips	Pieces	2	50	100
18.	Welding electrode (guage 10)	Packets	2	750	1500
19.	Welding and production work				20000
20.	Spraying				4000
21.	Transportation and miscellaneous expenses				45000
22.	TOTAL				₦190,700.00

The overall cost of producing the crucible furnace unit is One Hundred and Ninety Thousand Seven Hundred Naira (₦190,700.00) only.

III. RESULTS AND DISCUSSION

A. *Results*

Table 3: Test results of fabricated furnace with scrap aluminum

Cycles of heat	Aluminum			
	Charge materials mass (kg)	Temperature after complete melting (°C)	Volume of fuel used after complete melting (Litres)	Time (mins)
1st heat	5	650	0.9	18
2nd heat	5	660	1.1	16
3rd heat	5	645	0.8	13
Average	5	651.67	0.93	15.67

Table 4: Test results of fabricated furnace with scrap cast iron

Cycles of heat	Cast Iron			
	Charge materials mass (kg)	Temperature after complete melting (°C)	Volume of fuel used after complete melting (Litres)	Time (mins)
1st heat	5	1210	3.9	70
2nd heat	5	1217	4.4	115
3rd heat	5	1201	3.5	53
Average	5	1209.33	3.93	73.33

B. Discussions

From table 4.1 Five (5kg) of aluminum scrap after an average of three heat cycles used 0.93 litres of diesel to be completely melted at a temperature of 651.67°C in 15.67 mins, which satisfy the melting temperature (660°C) of aluminum [5].
From table 4.2 Five (5kg) of cast iron scrap after an average of three heat cycles used 3.93 litres of diesel to be completely melted at a temperature of 1209.33°C in 73.33 mins, which satisfy the melting temperature (1204°C) of cast iron [3].

IV. CONCLUSIONS

From the research the following conclusions were made:

A. A portable oil fired bale-out crucible furnace that melts cast iron and aluminum was designed successfully.
B. The furnace was produced using local materials.
C. The performance evaluation of the furnace shows that it successfully melted aluminum and cast iron scrap at 651.67°C and 1209.33°C respectively..

V. RECOMMENDATIONS

It is recommended that:

A. The furnace should be used, especially for small scale foundry workshop like Mechanical Engineering Workshop NDA.
B. Dual fired (two nozzles) should be incorporated to increase the heating rate of the furnace.

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APPENDICES

Appendix I: Pictures of the furnace produced

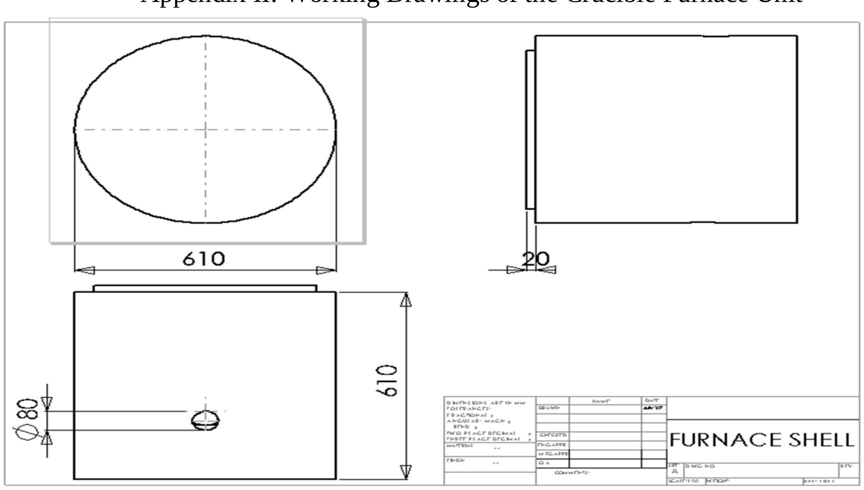
Fig. I furnace being charge

Fig. II furnace being heated

Fig. III Crucible after heating with molten cast iron

Fig. IV Furnace being heated.

Appendix II: Working Drawings of the Crucible Furnace Unit



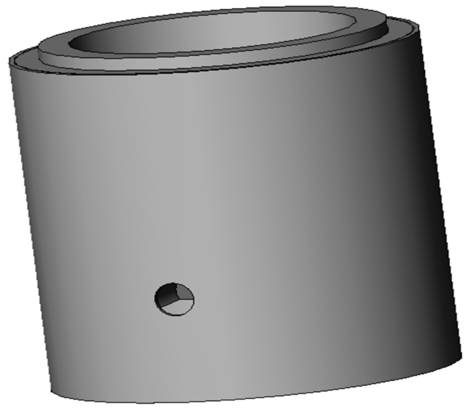
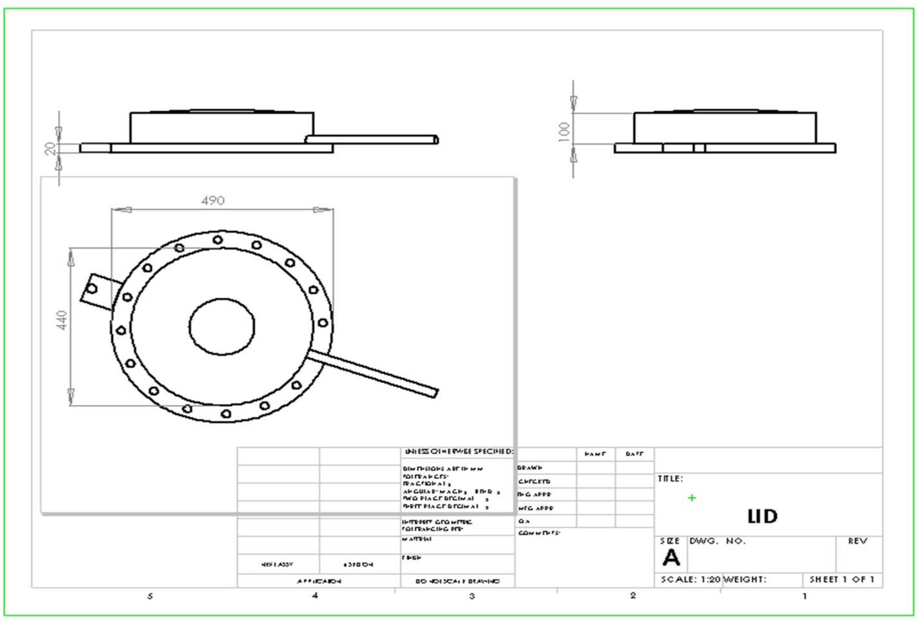


Fig. V: The Furnace drum (All dimensions are in mm)



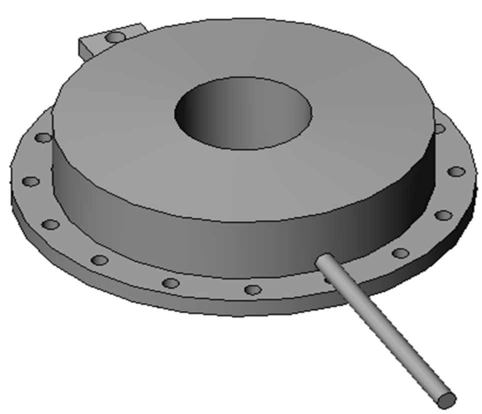


Fig VI: The Furnace Lid (All dimensions are in mm)

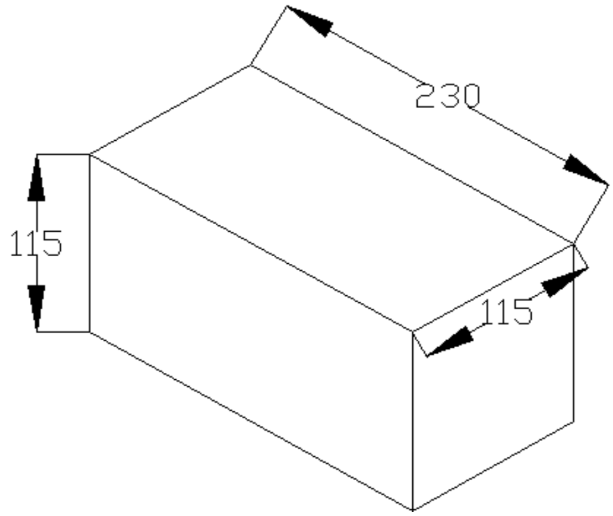


Fig VII: A Fire Brick (All dimensions are in mm)

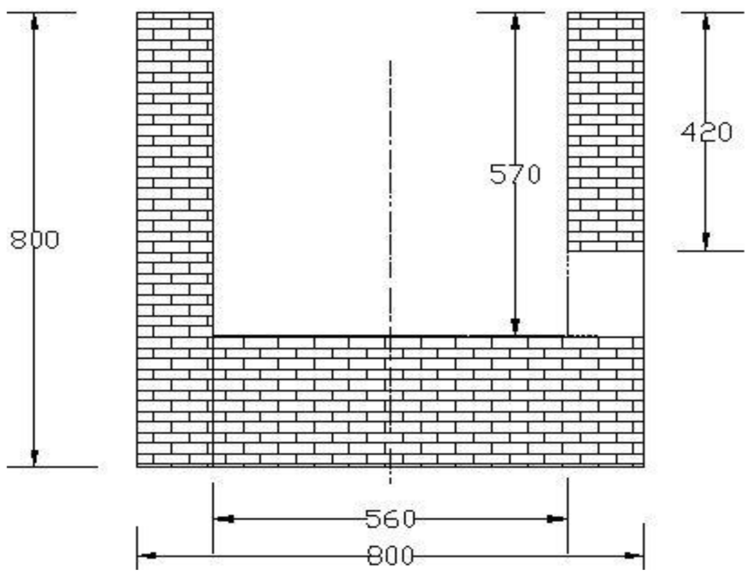


Fig. VIII: Furnace Wall Lined With Bricks (All dimensions are in mm)

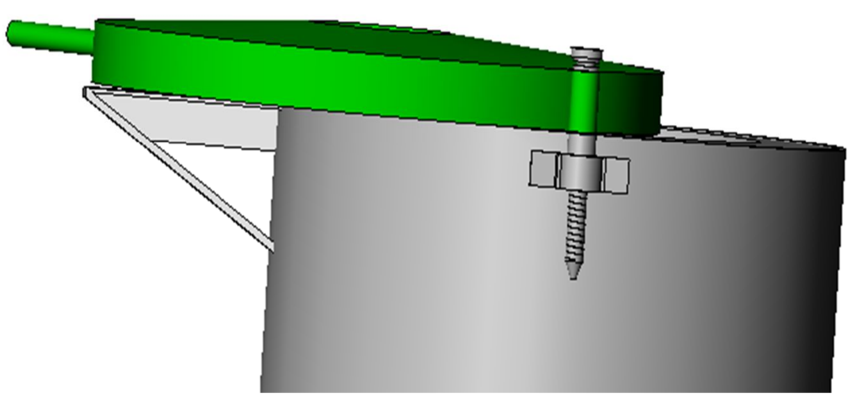


Fig IX: Furnace Cover's Opening/Closing Mechanism (All dimensions are in mm)

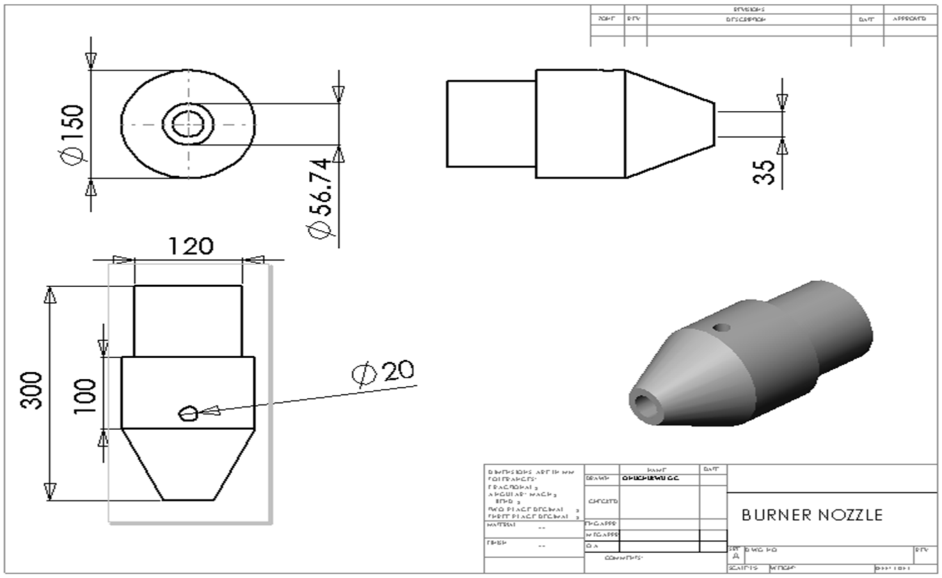


Fig. X: Nozzle (All dimensions are in mm)

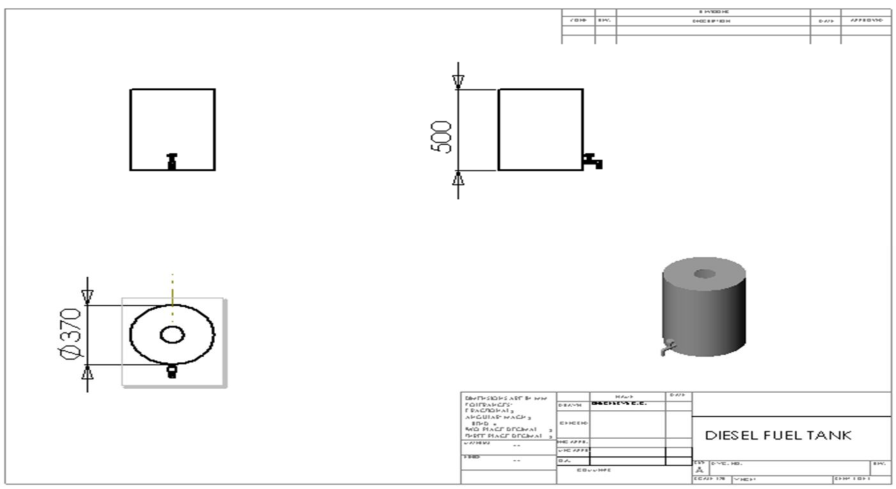


Fig. XI: Fuel Tank (All dimensions are in mm)

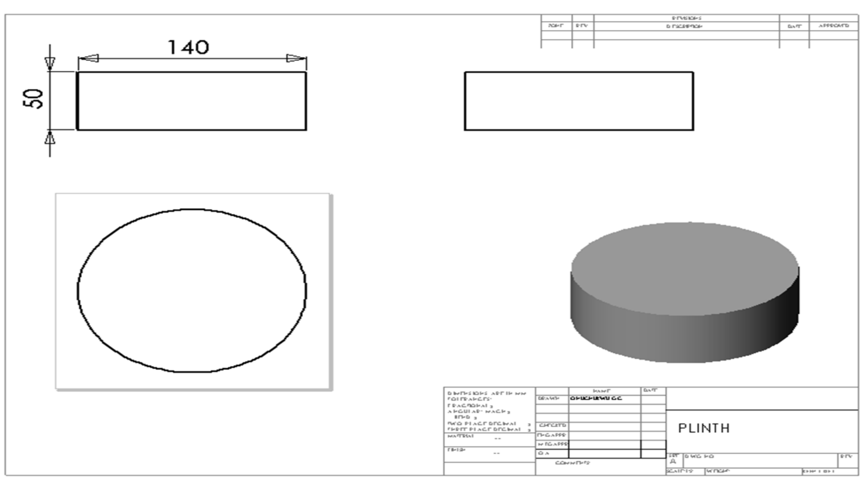


Fig. XII: The Plinth (All dimensions are in mm)

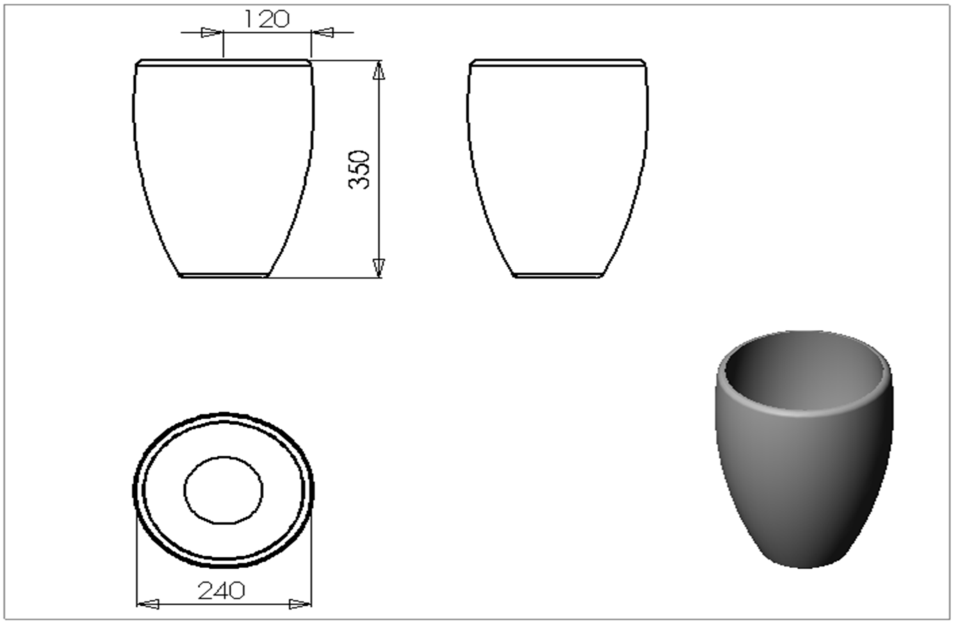
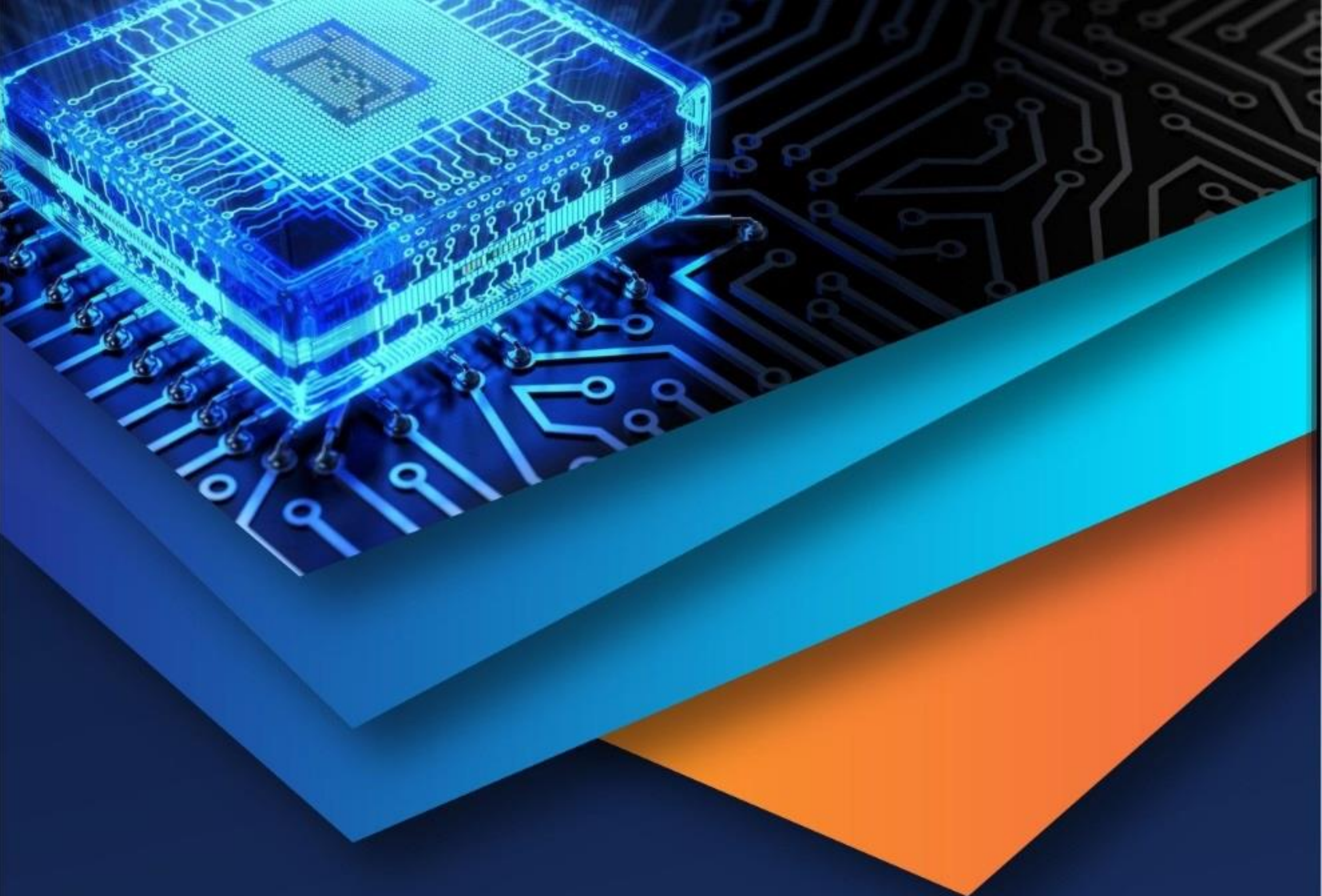


Fig. XIII: Crucible Pot (All dimensions are in mm)



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