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# Design and Construction of a Charcoal Furnace

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**ABSTRACT**: The research carried out a design and construction of a charcoal furnace. The study is focused onachieving a high efficiency in melting of aluminum, by properly minimizing heat losses, andmaximizing heat generation. In other to achieve this, a composite refractory material consisting of asbestos, cement, and clay in a ratio of 1:2:1 was used, and some charcoal was used to generate the heat, this generated a heat of 32.5 MJ at a working pressure of 0.262 Mpa. 20.05% of the heatgenerated was lost due its interaction with the environment change in the furnace geometry werenegligible indicating a long service life potential. With heat input of 25.98MJ, the furnace isable to melt 10kg of aluminum at a pouring temperature of 680$^0$C, leaving its efficiency at 79.94%. The design is considered to be safe since the working pressure does not exceed the working stress of itscasing.

**Keyword:** Charcoal, Furnace, Aluminium, Heat, Temperature, Pressure.

## I. INTRODUCTION

Blacksmith is an ancient and known trade to humans. With the increase in the use of metals because of their excellent mechanical properties, foundry operation keeps increasing. Aluminum is one of the most recycled metal world over,aluminum recycling is oneof the most lucrative business practices inNigeria and the world at large. This couldbe attributed to the fact that it takes lesseramounts of energy to produce aluminiumthrough recycling than through its ore. Therefore, it is necessary to harness every available source of energy to ensure that thebusiness of aluminum recycling in Nigeria,gains more ground. In trying to achieve thistask, the use of furnaces cannot beover emphasizedChukwudi, et al (2017).Afurnaceisa laggedenclosure designed primarily for heating ofmetals in order to achieve a metallurgicalchange. This change could either be torefine the microstructureofthemetalasinthe case of a heat treatmentfurnace,or itcould be to attain the pouring temperature ofthe metal as in the case of melting. It to thisend that this study intends to design andconstruct a charcoal furnace with the mainobjective of ensuring high efficiency inmelting of aluminum, by effectivelyminimizing heat losses, and maximizingheat generation.

However, these myriad of problems justify this project. The design has a lot of positive economic implications such as availability, maintainability, functionality etc. thus leading to comparative cost advantage over the imported ones. This will go a long way in assisting many local foundry industries and also conserve the limited foreign exchange due to the importation of furnaces and associated consumables, since Nigeria is enriched with varieties of these materials.

In Nigeria today, majority of foundry workshops uses the traditional furnace that is powered by charcoal which is outdated and time consuming and offers little production. This project when completed will give an alternative furnace that is more convenient and with high efficiency.

The project is going to cover the design, construction of the furnace. The materials for the construction is going to be sourced locally.

## II. DESIGN METHOD

In order to achieve the aim andobjectives of this study, the followingfactors were taken intoconsideration.Thesefactors include: material selection andavailability; dimension of furnace; designcriteria such as refractory wall thickness;working pressure; stresses set up in furnacewall; changes infurnacegeometry such as:height, diameter, area, and volume of the furnace, combustion reaction; beltdesign; heat supplied to the furnace, heatlosses by radiation, convection and conduction, insulat or effectiveness, efficiency of furnace; heat balance, melting capacity of the furnace.

**2.1 Crucible Refractory Brick wall**:This separates the crucible pot from the crucible casing. It functions to retain heat and prevents heat loss from the furnace to the casing via conduction. It also helps maintain

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high furnace temperature which enables complete fuel combustion. The refractory wall is a composite made up of Portland cement, asbestos and clay in a ratio of 2:1:1. Just like in the crucible casing, there is a vent of 200mm in diameter located at both the top side and bottom side ends of the wall. The bottom vent leads to the combustion chamber where air is blown. A groove of 50mm in width is created running along the inner part of the wall from the combustion chamber to the upper vent. This provides an escape route for the flue gases.

**2.2 Crucible**

The design is made to ensure that the charge to be melted is not in direct contact with the blowing heat but to serve as a medium to conduct heat generated from the blowing chamber which is transferred by convection to the charge. For this reason, the pot is made from chromium based steel which has high heat resistance, high strength and good thermal conductivity since it is exposed to direct heating. The pot has the following dimensions 10mm thickness, 140mm diameter and 200mm height.

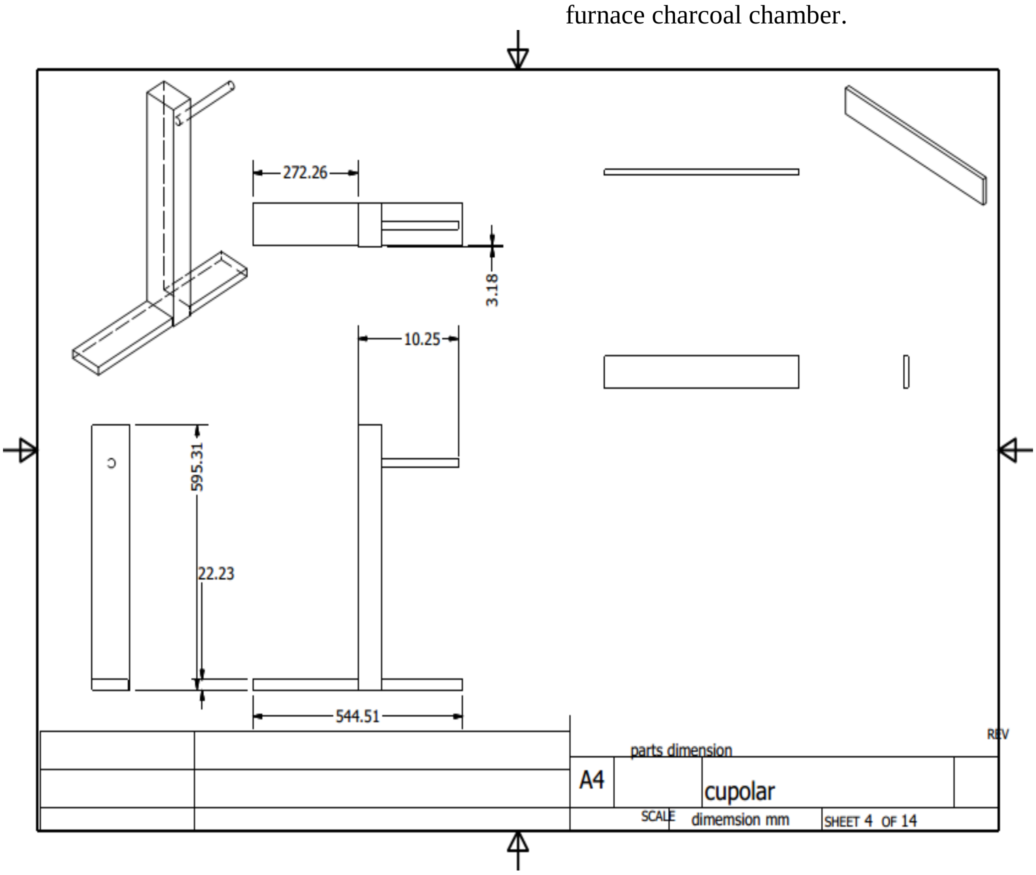
**2.3. Furnace cover**

The cover will be made from the 4mm thick steel it will be rolled into a cylinder of 485mm diameter, 65mm height with a hole of 175mm which serves as the exhaust.

**2.4. Furnace drum Design**

The furnace drum will be made from a mild steel plate of 4mm thickness by folding the mild steel plate into a cylindrical shape of 600mm diameter with the aid of a rolling/folding machine. A circular mild steel plate of diameter 600mm will be cut using a cutting machine and subsequently weld to the bottom of the folded drum with the aid of an arc welding machine. See the design drawing below.

**2.5. Crucible Casing:**This is the outermost partof the crucible furnace. It is made up of a 3660mm by 1525mm by 2.5mm sheet metal. Attached to it is a top cover which prevents heat loss by convection. It is also designed to have a 200mm vent at the upper end for the escape of flue gases and also another 200mm opening at the lower end for introducing the atomized fuel needed for combustion. This lower end leads to the furnace charcoal chamber.



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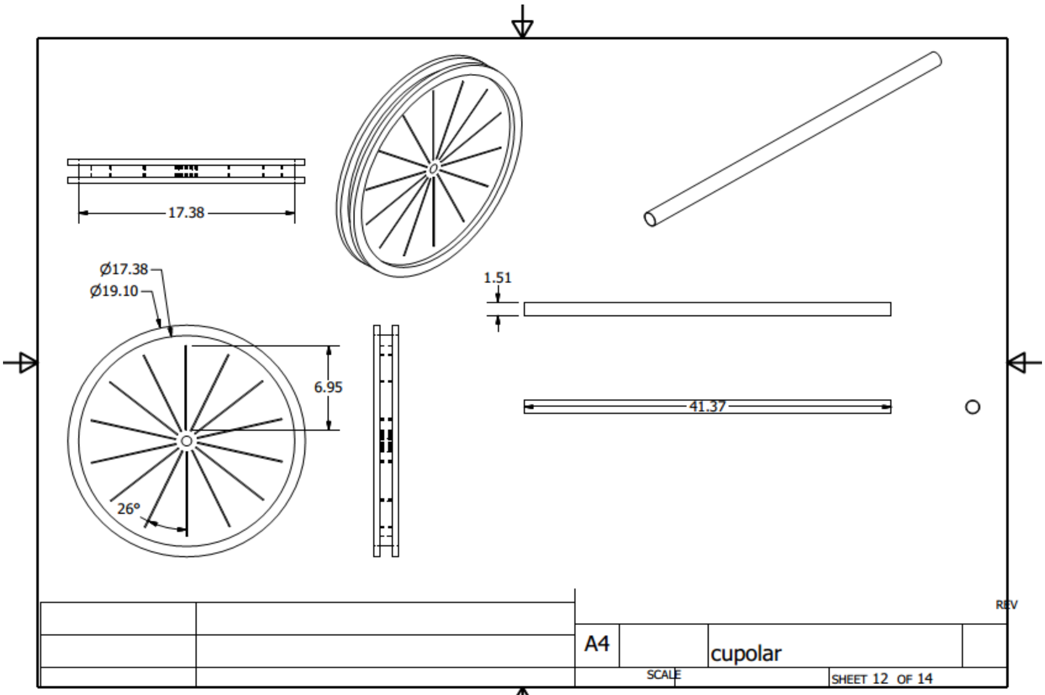


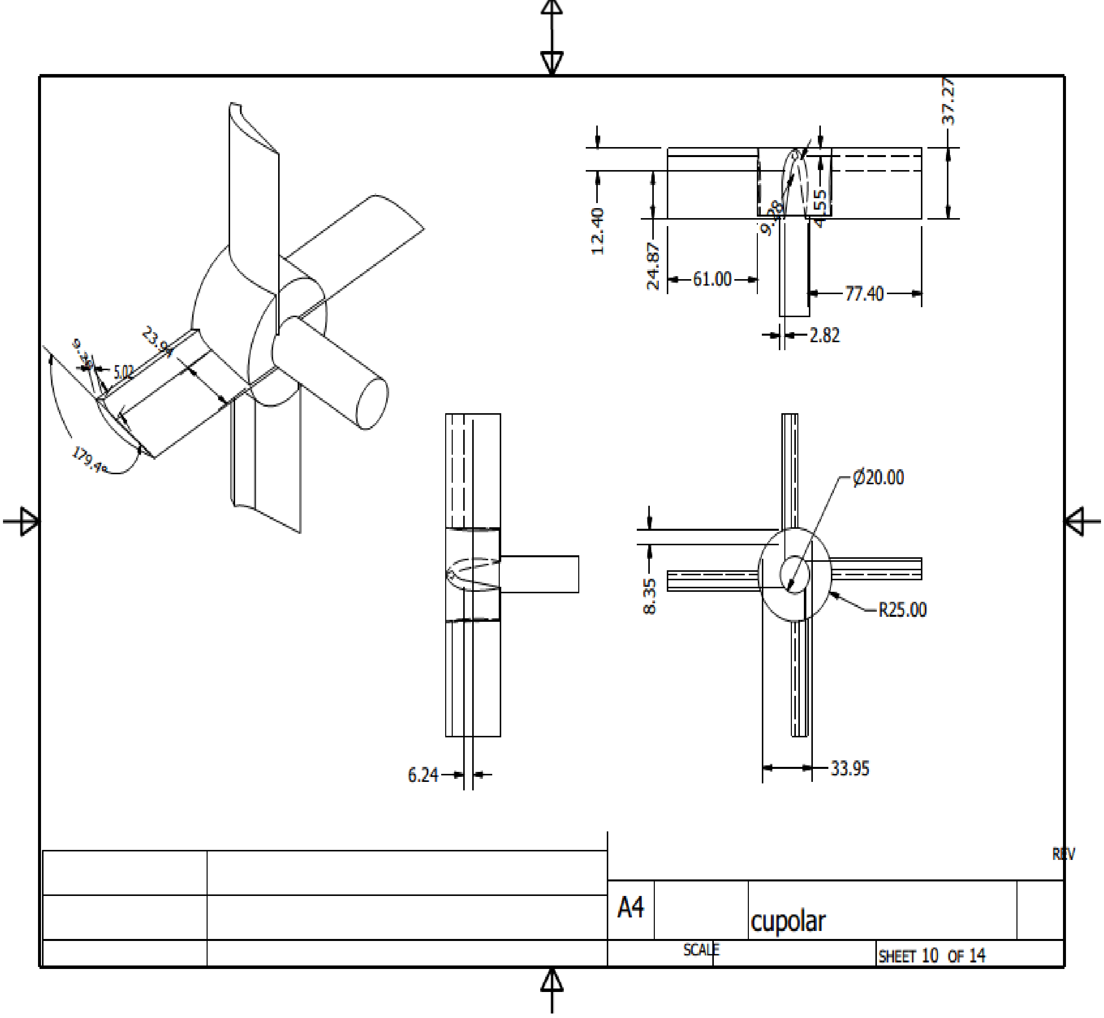

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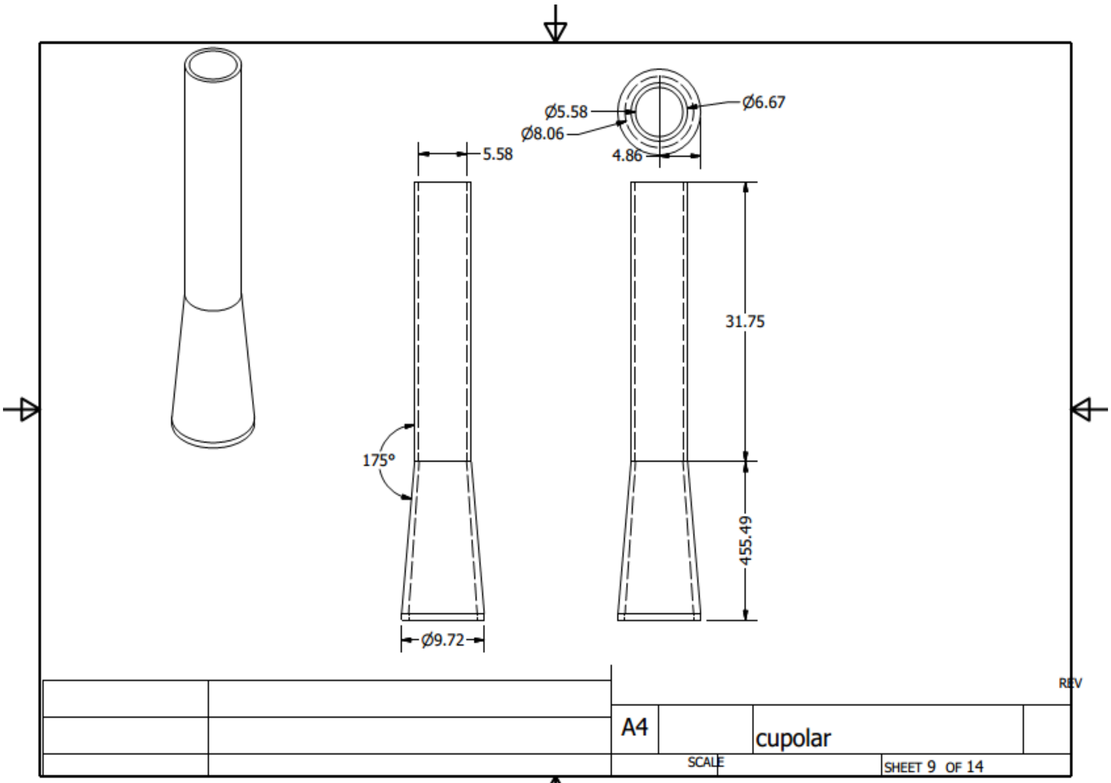


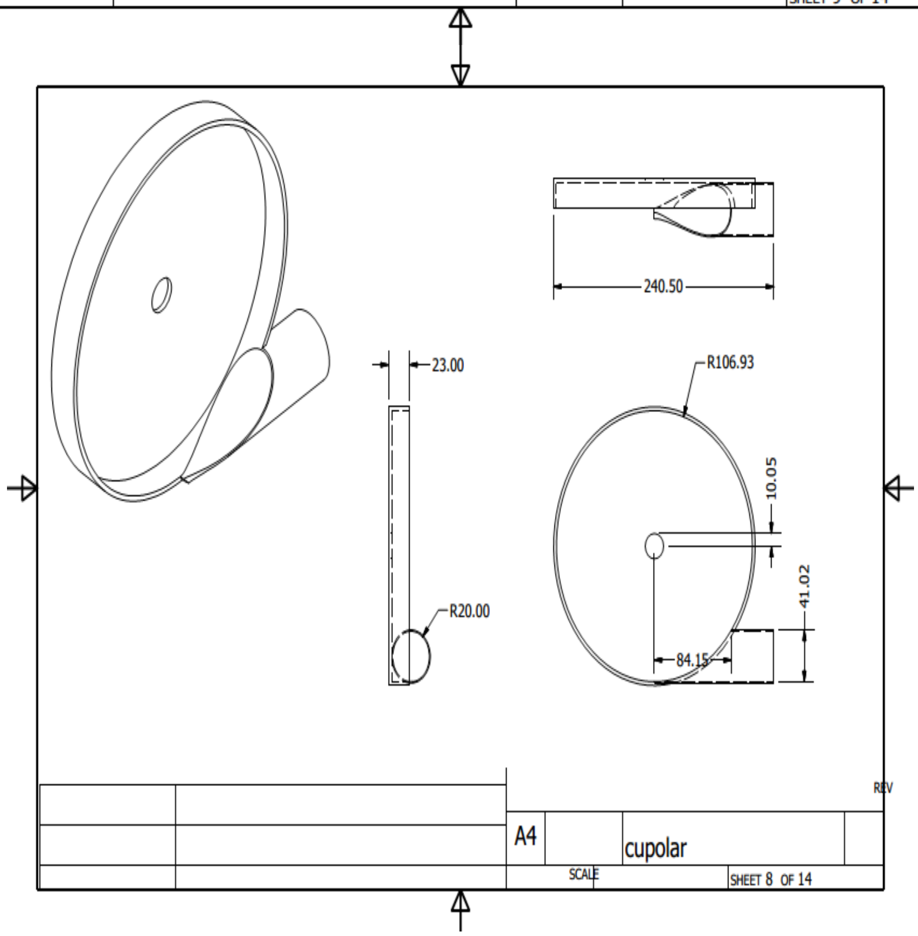

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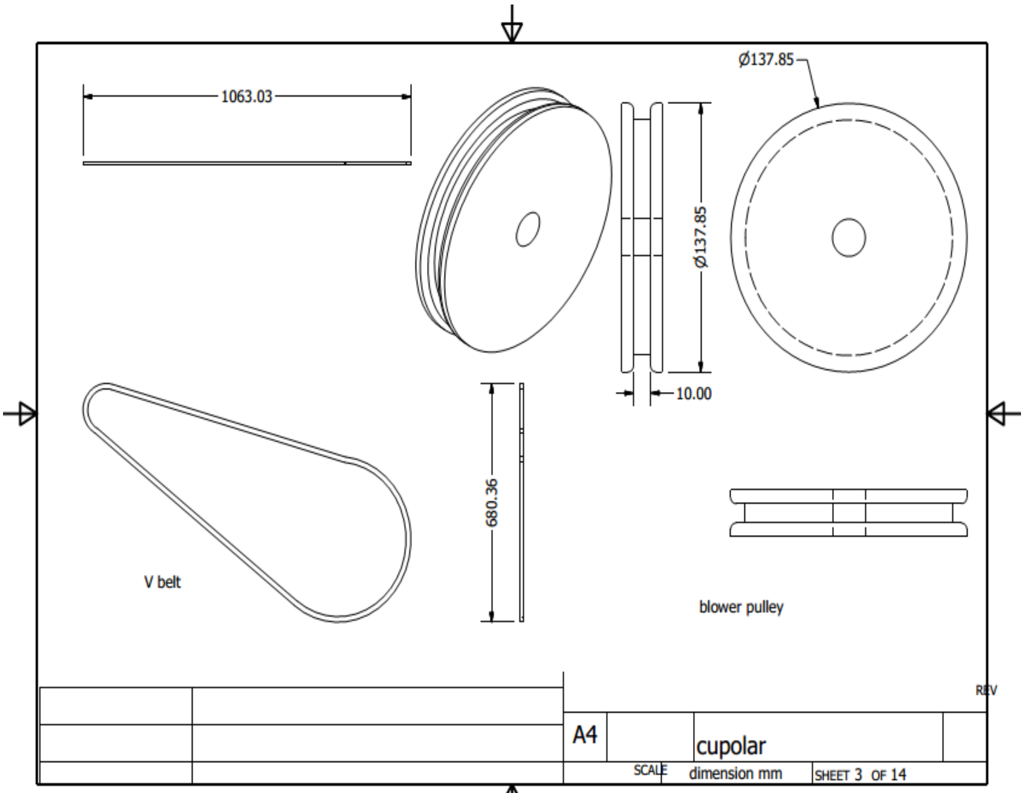


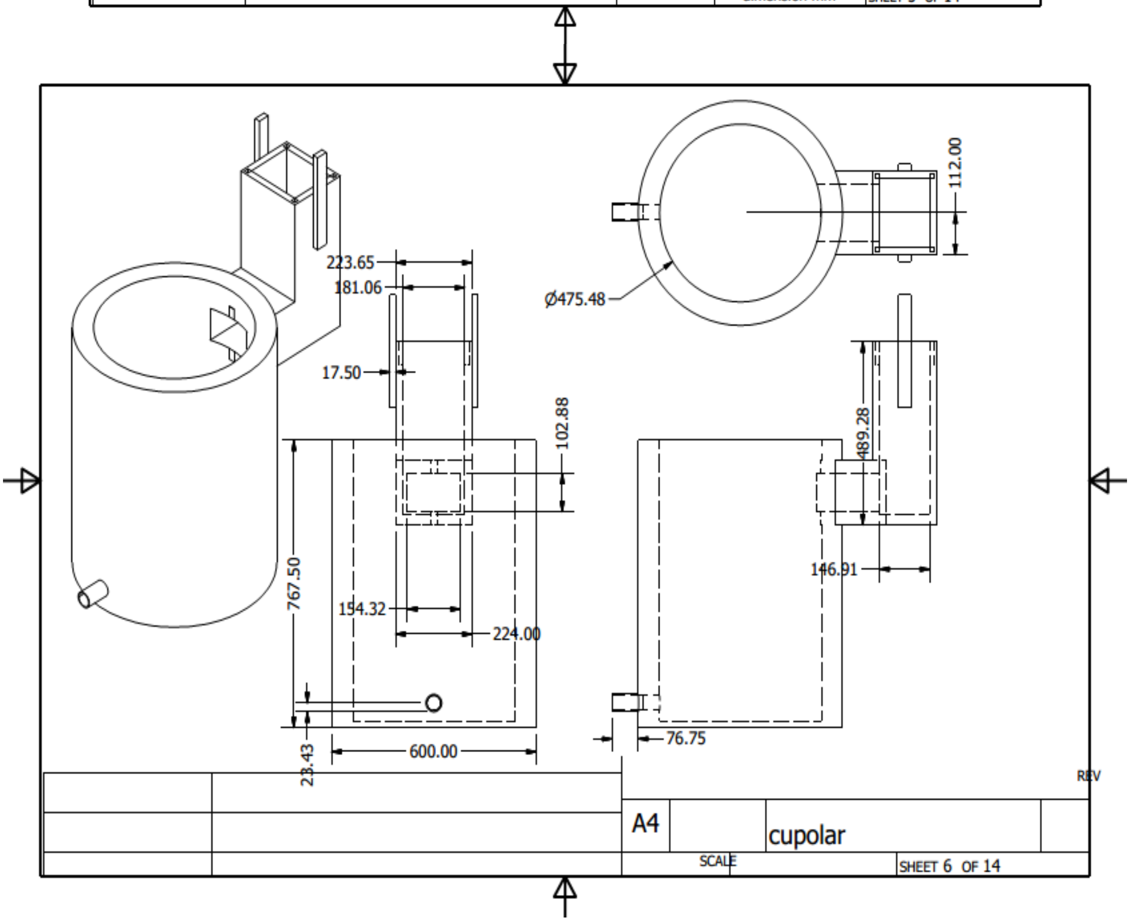

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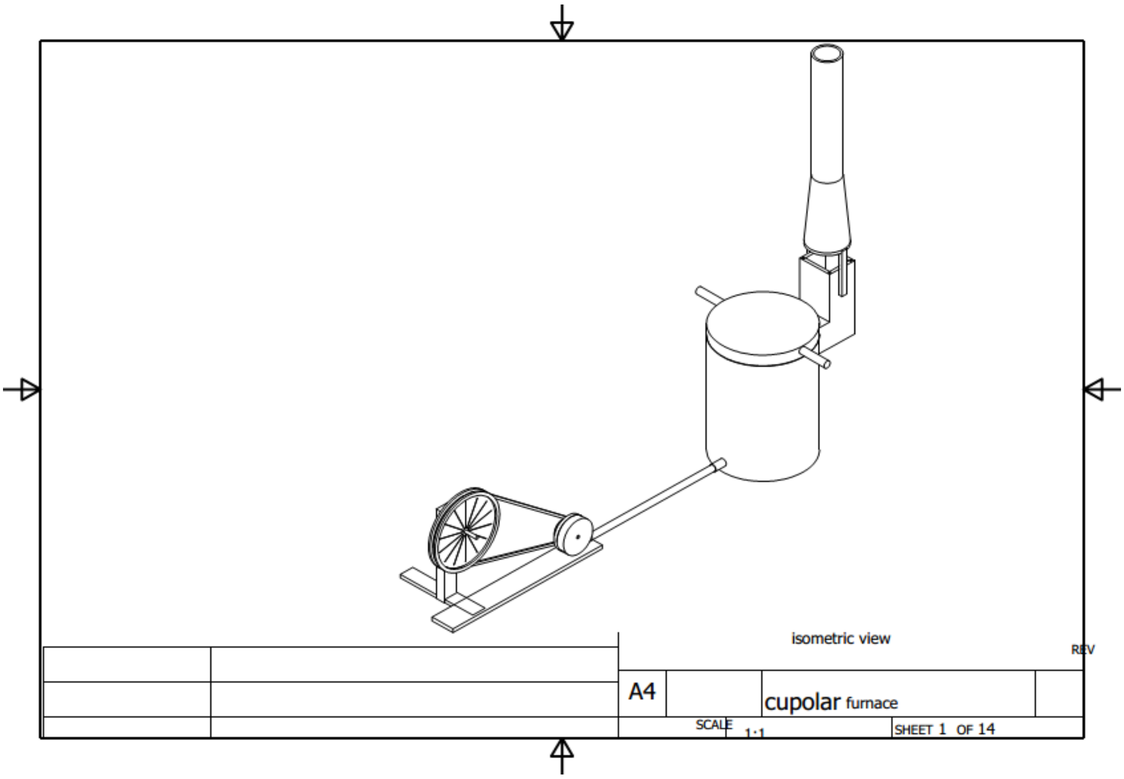


### 2.5 Design Criteria

**2.5.1 Working Pressure:**The pressure built up in the crucible furnace is as a result of the combustion of the air being blown into the hot charcoal. The flue gases which predominantly are $CO_2$ and $H_2O$ continually bombard the walls of the furnace,Date, A. W. (2011). The total working pressure is a function of the sum of the partial pressures of both gases. Assuming the flue gases to be ideal, the working pressure is obtained using equation 1.

$$P_{wp} = P_{CO_2} + P_{H_2O} \qquad (1)$$

Where: $P_{CO_2} = \frac{n_{CO_2}RT}{V}$, $P_{H_2O} = \frac{n_{H_2O}RT}{V}$,
V= volume, R= Universal gas constant, T= combustion chamber temperature.

**2.5.2 Refractory wall thickness:**In considering the pressure build up within the combustion chamber of the crucible furnace, the wall is considered to be thin shell pressure vessel since the thickness will not be more than 1/10 of its diameter size. The thickness of the wall can be determined using the equation put forward by Khurmi 2010, below.

$$t = \frac{Pr}{\tau\epsilon - P} + C$$

$$\tau = 0.57\sigma \qquad (2)$$

Where P = working pressure, R = radius of crucible walls,
$\epsilon$= joint efficiency, C = wear allowance,
$\tau$= shear strength, $\sigma$ = yield strength.

**2.5.3 Stresses set up in furnace wall:**Assuming that the heat generated within the combustion chamber occurs at a steady state, this will cause the furnace wall to be subject to stresses that act outwards from the combustion chamber, Singh, S. (2004). However, the crucible casing induces a compressive stress which counteracts the stresses within the furnace wall. Lame's equation is used to determine the tangential and radial stresses at the inner and outer walls of both the inner and outer cylinder.

$$\sigma_t = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} + \frac{r_i^2 r_o^2}{x^2}\left[\frac{P_i - P_o}{r_o^2 - r_i^2}\right] \qquad (3)$$

$$\sigma_r = \frac{P_i r_i^2 - P_o r_o^2}{r_o^2 - r_i^2} - \frac{r_i^2 r_o^2}{x^2}\left[\frac{P_i - P_o}{r_o^2 - r_i^2}\right] \qquad (4)$$

Where $P_i$, $r_i$, $P_o$, $r_o$, = Internal pressure, internal radius, external pressure and external radius respectively. $x$= radius of investigation.

**2.5.4 Furnace geometry changes:** The changes in the furnace height, diameter, area and volume due to the working pressure is expressed in equation 5 – 8.Khurmi 2005.For height,

$$\delta l = \frac{Pd}{4tE}(1 - 2\mu) \qquad (5)$$

For diameter,

$$\delta d = \frac{Pd^2}{4tE}(2 - \mu) \qquad (6)$$

For area,

$$\delta A = \frac{\pi}{4}(d+\delta d)^2 - \frac{\pi}{4}(d)^2$$
$$\delta A = \frac{\pi}{4}(2d\delta d + (\delta d)^2 \quad (7)$$

For volume,

$$\delta V = \frac{\pi}{4}(d^2\delta l + 2dl\delta l) \quad (8)$$

Where μ = Poisson's ratio, E = Young's modulus.

**2.5.5 Determination of open belt length:**put forward an expression for determining the length of an open belt, Khurmi (2010). This is sated as:

$$L_{approx} = 2C + 1.57(D+d) + \frac{(D+d)^2}{4C} \quad (9)$$

Where C = center distance = 630 mm, d=pitch diameter of smaller pulley= 60 mm, D=pitch diameter of larger pulley= 530 mm.

**2.5.6 Determination of the angle of contact or lap (ϴ):**the expression developed by Khurmi 2010, was used to determine the angle of lap.

$$\theta = (180° - 2\alpha)\frac{\pi}{180} rad \quad (10)$$

Where $\alpha$= angle between belt and center line **.**

**2.5.7 Velocity ratio of the belt drive:**This is expressed as

$$\frac{N_2}{N} = \frac{D}{d_1} \quad (11)$$

Where $N_1, N_2$represent speed of larger and smaller pulleys respectively.

**2.5.8 Torque transmitted by belt:**the torque transmitted by the belt drive is evaluated using equation 12.

$$T = (P_1 - P_2)r \quad (12)$$

Where $P_1$ = tension in belt "tight",$P_2$ =tension in belt "slack "and r = pulley radius.

**2.5.9 Heat generated:**The heat generated is a function of its quantity and the low calorific value of fuel.

Heat generated (Q) = M x LCV (14)

**2.5.10 Radiative heat loss through the vents:**The radiative heat loss through the furnace vents can be determined with the expression:

$$Q'_R = \sigma\varepsilon(T^4 - T_a^4) \quad (15)$$

Where: $Q_R$= heat loss by radiation through the exhaust vent, $T_g$= temperature of flue gas, $T_a$= temperature of ambient air,

$\sigma$ = Stefan – Boltzman constant = $5.669 \times 10^{-8}$Wm-2 K-4,

$\varepsilon$=total emissivity of outside surface. Assuming body to be a perfect emitter, $\varepsilon$= 1.

**2.5.11 Radiative heat loss to the refractory walls:**

It is expressed as $Q_R = \sigma A_{fT^4}$(16)

Where:

$A_f$= *Area of combustion chamber*

**2.5.12 Conductive heat loss due to insulation:**The heat loss due to insulation is expressed as

$$Q_C = -KA\frac{dT}{dx} \quad (17)$$

Where:

K=Thermal conductivity of refractory wall material

A=Surface Area refractory wall

**2.5.13 Conductive heat loss due to crucible pot:**This is the quantity of heat

$$dT = T - T_c$$
$$T_c = \text{furnace inner wall temperature}$$

absorbed by the crucible pot. It is expressed as

$$Q_C = -KA\frac{dT}{dx} \quad (18)$$

Where:

K=Thermal conductivity of crucible pot material

A=Surface Area of the crucible pot

$dT = T - T_c$ $dx$= insulation thickness.

$$T_c = \text{furnace inner wall temperature}$$

**2.5.14 Heat loss to furnace composite wall:**This heat loss is evaluated using the formula.

$$Q_w = \frac{(T_1 - T_0)}{\left[\frac{\left(\ln\frac{r_2}{r_1}\right)}{2\pi L_1 K_1} + \frac{\left(\ln\frac{r_3}{r_2}\right)}{2\pi L_2 K_2}\right]} \quad (19)$$

**2.5.15 Total heat loss:**This is the sum of all the heat losses that occur in the furnace.

$$Q_l = Q_R + Q_C + Q_R + Q_C + Q_w + Q_f \quad (20)$$

**Useful heat:** This is heat used up in melting aluminum.

$$Q_u = Q - Q_l \quad (21)$$

**2.5.16 Furnace efficiency:**it's a ratio of the utilized heat to the heat input.

$$\eta = \frac{\text{Useful heat } (Q_u)}{\text{Heat generated } (Q)} \quad (22)$$

**2.5.17 Heat flux:**The heat flux is calculated using equation 23.

$$q = \frac{T_i - T_0}{R_{Th}} \quad (23)$$

Where $R_{Th}$= is the total thermal resistance of the wall.

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$$R_{Th} = \frac{t_{refractory}}{K_{refractory}} + \frac{t_{casing}}{K_{casing}}$$

**2.5.18Mass of Aluminum:**the mass of aluminum that can be melted per session can be expressed as

$$M_{Al} = \frac{Q}{C_p(T_p - T_a)} \quad (24)$$

Where $T_p$= pouring temperature of aluminum.

## III. RESULTS

The results of the design analysis is displayed in table 1

**Table 3**: Design Results

| Parameter | Value |
|---|---|
| Working Pressure | 0.262 MPa |
| Refractory wall thickness | 15 mm |
| Tangential Stress | |
| Tangential stress when x =$r_i$ | 103.06 GPa |
| Tangential stress when x=485mm | 103.05 GPa |
| Tangential stress when x=$r_o$ | 94.97 GPa |
| Radial Stress | |
| Radial stress when x=ri | -103.06 GPa |
| Radial stress when x=485mm | -103.05 GPa |
| Radial stress when x=ro | -94.97 GPa |
| Geometry Changes | |
| Change in length | 1.35x10-5 mm |
| Change in diameter | 5.8x10-2 mm |
| Change in area | 6.77x10-4mm |
| Change in volume | 1.58x10-2mm |
| Belt Design | |
| Length of belt | 2274 mm |
| Angle of lap | $3.128^0$ |
| Belt drive velocity ratio | 9:1 |
| Torque | 26.71 N |
| Heat calculations | |
| Heat generated | 32.5 MJ |
| Heat Losses | |
| Radiation through vents | 59.65 Kj |
| Convection through vent | 12.57 J |
| Radiation to wall | 25.584 kJ |
| Conduction to wall | 2.194 Kj |
| Conduction crucible pot | 7.47 MJ |
| Loss to composite wall | 31.13 kJ |
| Flue gas | 85.41 kJ |
| Total heat loss | 7.66 MJ |
| Useful heat | 25.98 MJ |
| Furnace efficiency | 79.94% |
| Heat flux | 161.81 W/m2 |
| Mass of aluminum | 10 kg |

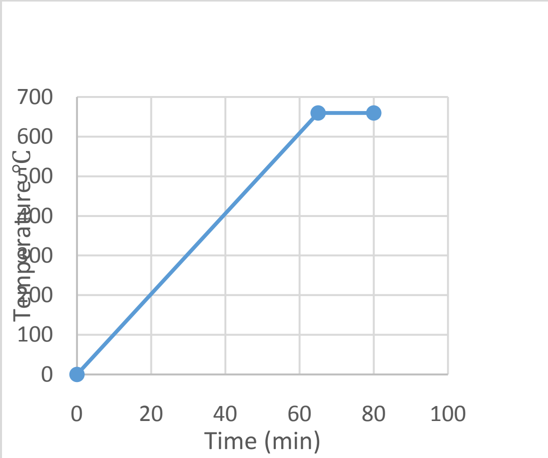


**Figure1**. graph of melting temperature of Aluminium against Time

## IV. DISCUSSION

From the results presented in table 3,it is seen that the working pressure with in the combustion chamber is four times morethan the atmospheric pressure, and as a result it would exert pressure on the wall ofthe refectory. The stress the workingpressure sets up in the wall is counteract by the compressive stress exerted on thewall by the crucible casing. Hence, with thetangential (tensile) and radial (compressive) stresses being equal, an equilibrium isattained. Also, the design is considered to besafe since the value of the working stress ofsteel which is approximately 200 MpaB.E.E (2016), is greater than the working pressure. Thisimplies that the thickness of the furnace willwithstand failure. From figure 1, it took the furnace 55minutes to reach the melting temperature of 660°C and further 15minutes to completely melt.

## V. CONCLUSION

The study carried out a design andconstruction of a charcoal crucible furnace.The main objective of the study is to useensure high efficiency in melting ofaluminum, by effectively minimizing heatlosses, and maximizing heat generation. Hence, the uses of available local materialswith good insulating properties werecarefully selected for the refractory wall. Through this process, 32.5 MJ of heat is generated. 20.05% ofthe heat generated was lost due itsinteraction with its environment. Changes inthe furnace geometry were negligibleindicating a long service life potential. The useful heat input is 25.98 MJ, it took thefurnace a total of 80 minutes to melt 10kg of aluminum at apouring temperature of $660^0$C,with anefficiency of 79.94%.

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