

# Design and Thermal Analysis of Crucible Furnace for Non – ferrous Metal

Olenyi Joseph Oghenekaro Peter Joseph Michael Irabodemeh\* Sheidu SumailaOnimisi  
National Engineering Design Development Institute Nnewi, AnambraState, Nigeria. P.M.B 5082

## Abstract

The advancement of any nation technologically has been influenced and elevated by the extent to which it can usefully harness and convert its mineral resources. The productions of metal in foundries and in all human lives have also become a general practice. Different melting techniques are in practice with different energy sources, hence the need to analyzing the heat flow in the crucible furnace during melting operation of the scraps in the crucible pot of the furnace. This paper focuses on the analysis of transient and steady state of heat flow across the entire area of the inside furnace by employing Granter CesEdu pack, 2011 for materials selection, Creo element for geometry development of the furnace and Ansys 14.0 for the thermal analysis. From the analysis the maximum total heat flux is  $1275200\text{w/m}^2$  which is found inside the region of the furnace and a minimum of  $3.9833\text{e}^{-12}\text{ W/m}^2$  at cold outer region of the furnace, also the positive heat flux of  $835740\text{w/m}^2$  inside the system and heat loss to the surrounding of  $761420\text{w/m}^2$  were obtained at point of heat supply channel.

## 1. INTRODUCTION

In the production of mineral resources, the melting of metals has become one of the tremendous industrial practices in the forefront. This is because metals are versatile elements whose fields of applications are very wide in human lives. Of all metals, iron production has developed substantially, such that different types of furnaces ranging from blast furnaces, open-hearth furnaces, to converters and electric furnaces for steel production are in use today worldwide. Ajaokuta Steel Company and Delta Steel Company are examples of steel making companies in Nigeria that use these types of furnaces. Aluminum being the most abundant metallic element, forming about 8% of the solid portion of the earth's crust, is rarely available as rich ores. Hence most countries are dependent on supplies of it being imported. Nigeria, for instance, uses aluminum in all aspects of human endeavor, be it transportation, machine components, cooking utensils alloying etc. these components display a marked decrease in performance level after some years of service and have to be discarded (Adeosun, S.O. & Osoba, L.O, 2008).

The re-melting of these scraps product of aluminum will go a long way to enhance the availability of the product without over reliance on the foreign market, and thereby improving the foreign reserve. Similarly, the acquisition of melting equipment for this purpose has also become a very difficult thing such that there is a need to look inward for fabrication of some vital components for our technological growth. It is in view of this, that different methods of melting aluminum are being used in the country, such as crucible furnaces, either on industrial or local small scale. Therefore, Crucible furnace is a furnace used for melting non-ferrous metals.

The crucible furnace consists basically of a crucible, cylindrical metal sheet. The crucible holds the charged materials and subsequently the melt. The choice of refractory material depends on the type of charge, i.e. acidic, basic or neutral. In this design a neutral refractory is use and based on effectiveness, availability and practical application in Nigerian foundries, alumina ( $\text{Al}_2\text{O}_3$ ) is implored. The durability of the crucible depends on the grain size, charge analysis and rate of heating and cooling the furnace. The cylindrical metal sheet is the outer part of the furnace. This houses the crucible and the refractory lining.

The furnace is the most important equipment used in the foundry industry, which is an industry that uses logical methods for shaping metals. Almost all industries rely on castings products whose productions are impossible without the furnace. Examples of industries that depend on foundry industry are Automobile, Machine tools, Aerospace, Electrical, Plumbing, Communication etc as reported by Asibeluo I.S (2015).

Asibeluo and Ogor (2015), designed a 50-kilogram capacity Cast-iron crucible furnace that is fired with diesel fuel. The furnace drum has an overall combustion capacity of  $0.1404\text{m}^3$ . It is fitted with a chimney to allow for the easy escape of combustion gases. The air blower discharge air into the furnace at the rate of  $0.3\text{m}^3/\text{s}$  with an air/fuel ratio of 400:1. The cast-iron crucible furnace is designed to consume four gallons of diesel fuel with a rating of  $139000\text{kJ/gallon}$  which is required to completely melt 50-kilogram of cast iron over a period of 90min. The designed operation temperature range of the cast-iron crucible furnace is  $13000\text{C}$  to  $14000\text{C}$ .

Bhat et al (2012) carried out thermal analysis of induction furnace, the mock-up induction furnace was modeled in COMSOL Multiphysics. Prior to that the Induction Heating Interface algorithm under the Heat Transfer Module of COMSOL Multiphysics was validated with the experimental data. The results of the study shown that the temperature of the crucible rises to  $1500^\circ\text{C}$  in 2 hours of heating time at frequency of 8 kHz and current of 400 A. The conditions were favorable for melting of copper (melting point =  $1085^\circ\text{C}$ ) in the crucible

Ogunrinola, G.O. (2000) and RMRDC report (2003) independently argued that the development of the foundry industry in Nigeria has suffered several set-backs such as lack of stable electrical power supply, high cost

of importation of foreign furnaces, raw materials etc. which had resulted to low production output, loss of man hours, high cost of production, and in most cases, loss of jobs occasioned by closure of most of the industries. There are about 160 foundries in Nigeria at different stages of life and death conditions and they meet less than 5% of Nigeria's demand for machine components and mechanical parts (Adeosun, S.O. & Osoba, L.O, 2008). Therefore, this study focuses on transient and steady analysis of a heat flow in a crucible furnace for non-ferrous metals during melting operation.

## 2. Methodology

The steady state heat analysis of the furnace was studied with ANSYS 14.0 where the materials for the engineering brick and crucible were assigned to the geometry. It was subjected to a temperature of 800°C which was considered to be pouring temperature for aluminum melt. The temperature distribution, total heat flux and directional heat flux were investigated. The total mass of the crucible furnace is 1579kg.

**Table1: Material properties for bricks and crucible**

Materials	Thermal Conductivity (W/ m °C)	Density (kg/m <sup>3</sup> )	Specific Heat (J /kg C)
Ceramics bricks	4.5	4900	800
Cast Iron	83	7200	165

Source: ANSYS 14.0 Material Data

### 2.1. Design Analysis and Materials Selection

#### Geometrical parameters

The analysis is based on a 120kg capacity. The shape of the crucible is cylindrical. The internal diameter of the crucible and the height of melt are determined by the furnace capacity (melt volume).

### 2.2. DESIGN CALCULATIONS OF A CRUCIBLE FURNACE

#### Specifications

Height of crucible = 650mm

Width of crucible = 450mm

Thickness of crucible = 50mm

Taper bottom portion = 300mm

Density of bricks used = 4900kg/m<sup>3</sup>

Density of mild steel = 7860 kg/m<sup>3</sup>

For a bricks that has a dimension of 230mmx115.9mmx65mm

Its volume is = 0.23m x 0.1159m x 0.065m = 0.0017m<sup>3</sup>

From  $density = \frac{mass}{volume}$

mass of one brick = density x volume of one brick = 4900 x 0.0017 = 8.33kg

Weight of one brick = mg = 8.33 x 9.81 = 81.71N

#### Calculations for the internal and external diameter of the furnace.

Since the width of the crucible = 450mm,

The space between the crucible and the walls of the furnace for both sides = 200mm each, also, the thickness of the brick is 65mm.

Therefore, the internal diameter of the furnace is got as follows

450mm + 200mm + 200mm = 850mm

Therefore, the internal diameter ( $\phi_i$ ) = 850mm

For the external diameter ( $\phi_E$ ) = internal diameter + thickness of the refractory bricks

External diameter ( $\phi_E$ ) = 850mm + 65mm + 65mm + 65mm + 65mm = 1110mm

#### Calculations for the internal and external height of the furnace

Internal height of the furnace = height of crucible + one and half height of bricks

Therefore, internal height of furnace = 650mm + 230mm + 115mm = 995mm

External height = internal height of furnace + thickness of two bricks + metal sheet thickness

Therefore, external height = 995mm + 130mm + 5mm = 1130mm

#### Circumference of the furnace

The circumference of the furnace =  $2\pi r$

Where r = radius of the internal diameter of the furnace =  $\frac{950mm}{2} = 425mm$

Hence, the Circumference =  $2 \times \frac{22}{7} \times 425 = \frac{18700}{7} = 2671.4mm$

**Calculating the numbers of bricks that could seat and stand in the furnace**

**Numbers of bricks that could be seating**

Since the circumference of the furnace gave 2671mm

$$\text{Therefore, Seating bricks} = \frac{2671\text{mm}}{\text{length of the bric}} = \frac{2671\text{mm}}{230\text{mm}} = 11.61 \approx 12 \text{ bricks in one layer}$$

Since there are two layers at the bottom, 24 bricks would be needed at the bottom of the furnace.

**Numbers of bricks that could be standing**

$$\text{Standing bricks} = \frac{2671\text{mm}}{\text{height of brick}} = \frac{2671\text{mm}}{115.9} = 23.0 \text{ 5bricks} \approx 23 \text{ bricks}$$

46 bricks would be needed to stand round the furnace for the first layer

**Calculating the total numbers of standing bricks that could be used for all the layers in the furnace**

Internal height of the furnace-thickness of the brick at the bottom of the furnace

$$995\text{mm} - (65 \times 2)\text{mm} = 995\text{mm} - 130\text{mm} = 865\text{mm}$$

$$\text{Therefore, the numbers of layers of bricks} = \frac{865\text{mm}}{230\text{mm}} \approx 4 \text{ layers}$$

Hence, total numbers standing bricks that would be needed to round the furnace =  $4 \times 46 = 184$  bricks

**Calculating weight of the bricks**

Recall from 1.1 from above, that the weight of one brick is 81.71N

Also, the total numbers of bricks to be used in the furnace lining=232 bricks i.e. 184 bricks standing plus 48 bricks both at the bottom and top cover of the furnace.

$$\text{Therefore, total weight of the bricks in the furnace} = 232 \times 81.71 = 18,956.72\text{N} \approx 18.96\text{KN}$$

**Calculating for the weight of the metal sheet of the furnace**

Recall that the volume of a cylinder=  $\pi r^2 h$

$$\text{Volume} = (\pi r^2 h)_{\text{external}} - (\pi r^2 h)_{\text{internal}}$$

$$\text{Volume} = (3.142 \times 0.555^2 \times 1.13) - (3.142 \times 0.425^2 \times 0.995)$$

$$\text{Volume} = 1.0936 - 0.5647 = 0.5289\text{m}^3$$

Recall again that,  $\text{density} = \frac{\text{mass}}{\text{volume}}$

The metal used here is mild steel and as such its density is  $7.860 \times 10^3 \text{kg/m}^3$

$$\text{Mass} = \text{density of mild steel} \times \text{volume} = 7860 \times 0.5289 = 4157.154\text{kg} \approx 4157\text{kg}$$

$$\text{Weight of the cylindrical metal sheet (mild steel)} = mg = 4157 \times 9.81 = 40780.17\text{N} \approx 40780\text{N} = 40.78\text{KN}$$

**Calculating weight of the crucible**

Since the crucible to be used is 120kg

$$\text{Hence, its weight} = mg = 120 \times 9.81 = 1177\text{N} = 1.177\text{KN}$$

**Calculating the weight of the furnace cover**

$$\text{Density of the brick used} = 4900 \frac{\text{kg}}{\text{m}^3}$$

$$\text{Volume of one brick} = 0.0017\text{m}^3$$

$$\text{Since 24 bricks would be used at the cover, we have that its volume} = 24 \times 0.0017 = 0.0408\text{m}^3$$

$$\text{Mass of the furnace cover} = \text{density of brick} \times \text{volume of brick} = 4900 \times 0.0408 = 199.92\text{kg}$$

$$\text{Its corresponding weight} = mg = 199.92 \times 9.81 = 1.96\text{KN}$$

**Calculating weight of the molten metal**

Let mass of charged materials equals mass of the molten metal= 100kg

$$\text{Therefore, its weight} = 100 \times 9.81 = 981\text{N} = 0.981\text{KN}$$

**Calculating the gross weight of the furnace**

**Gross Weight**=weight of bricks + weight of metal sheet of furnace + weight of crucible +weight of furnace cover + weight of molten metal

$$\text{GROSS WEIGHT} = (18.96 + 40.78 + 1.177 + 1.96 + 0.981)\text{KN} = 63.86\text{KN}$$

**3. Thermal analysis**

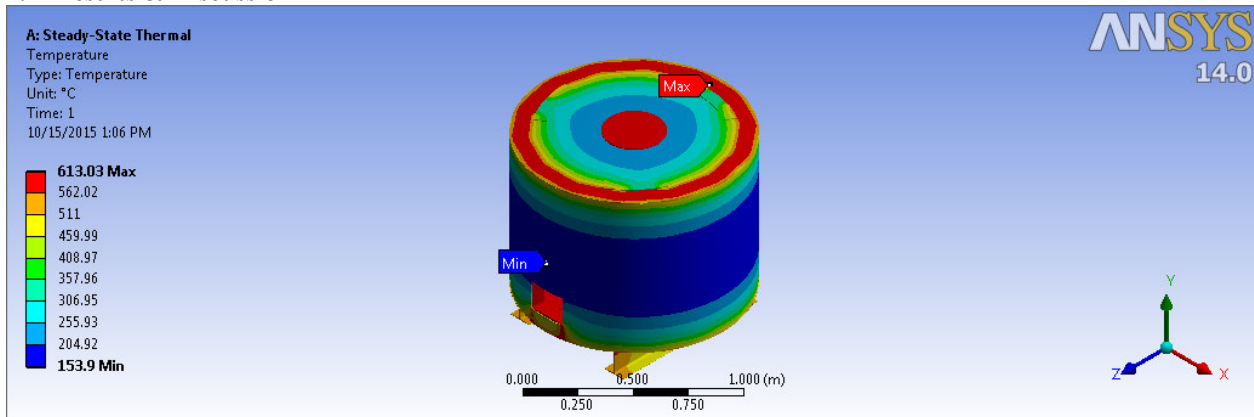
The amount of heat (q) flowing from one location to another is proportional to:

- i. Thermal conductivity k
- ii. Cross sectional area A through which it flows and
- iii. Temperature gradient  $\frac{dT}{dx}$

This is expressed in the below formula as

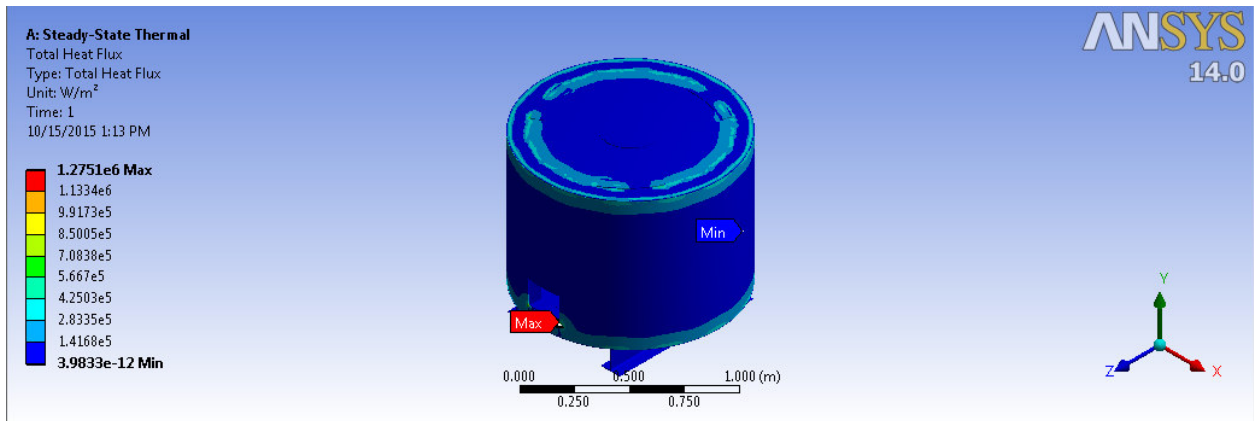
$$q = kA \left( \frac{dT}{dx} \right) \text{-----(Rees, 2008)}$$

#### 4. Results & Discussion



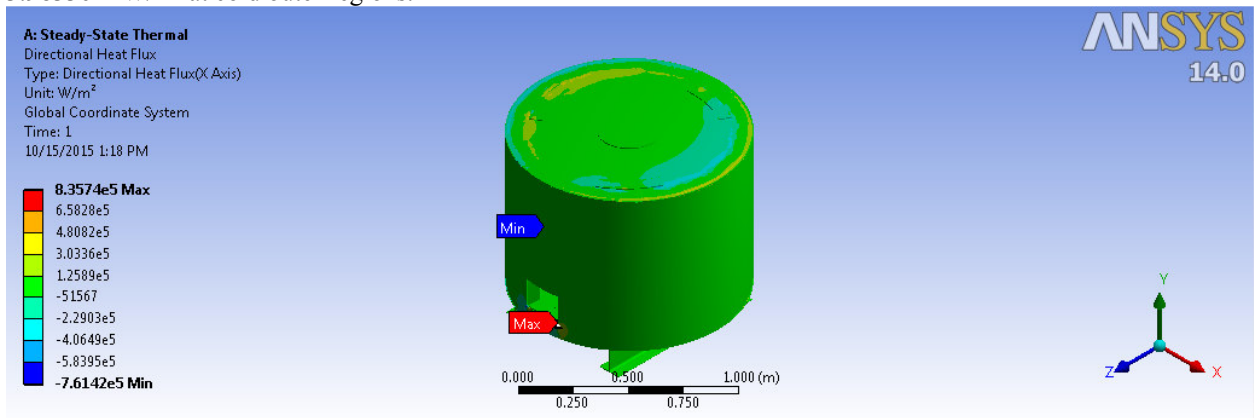
**Figure1: Temperature distribution**

The red portion shows the hottest part in the furnace during melting operation with a temperature of 613°C. This area is found inside the furnace, bottom and top of the furnace. This is as a result of direct heat application. The cold region marked by blue colour has the minimum temperature of 154°C. These areas are not directly exposed to source of heat.



**Figure 2: Total heat flux**

The system has a maximum total heat flux of 1275200 W/m<sup>2</sup> in inside the furnace and a minimum of 3.9833e<sup>-12</sup> W/m<sup>2</sup> at cold outer regions.



**Figure3: Directional Heat Flux**

The positive heat flux of 835740 W/m<sup>2</sup> and heat loss to the surrounding of 761420 W/m<sup>2</sup> were obtained at point of heat supply channel.

**Table2: Steady state parameters studied with their Maximum and minimum values.**

S/N	Parameter	Maximum Value	Minimum Value
1	Temperature Distribution ( °C )	613.03	153.9
2	Total Heat Flux (w/m <sup>2</sup> )	1.2751e <sup>6</sup>	3.9833e <sup>-12</sup>
3	Directional Heat flux (w/m <sup>2</sup> )	8.3574e <sup>5</sup>	-7.6142e <sup>5</sup>

## 5. Conclusion

A detailed design of crucible furnace and its steady state thermal analysis with ansys 14.0 has been carried out. The material selections were carefully made so as to enable it perform the function it was designed for. It was constructed according to the design specifications.

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