American Journal of Mechanics and Applications
2017; 5(3): 15-21
http://www.sciencepublishinggroup.com/j/ajma
doi: 10.11648/j.ajma.20170503.11
ISSN: 2376-6115 (Print); ISSN: 2376-6131 (Online)

Development of a 30Kg Aluminium Oil-Fired Crucible Furnace Using Locally Sourced Materials

Adeodu Adefemi, Daniyan Ilesanmi, Babalola Simeon, Okojie Favour, Aderoba Adeyemi

Department of Mechanical and Mechatronics Engineering, AfeBabalola University, Ado-Ekiti, Nigeria

Email address:
adeoduac@abuad.edu.ng (Adeodu A.), afolabiilesanmi@yahoo.com (Daniyan I.), babalolasa@abuad.edu.ng (Babalola S.), babalotujama@yahoo.com (Aderoba A.)

To cite this article:
Adeodu Adefemi, Daniyan Ilesanmi, Babalola Simeon, Okojie Favour, Aderoba Adeyemi. Development of a 30Kg Aluminium Oil-Fired Crucible Furnace Using Locally Sourced Materials. *American Journal of Mechanics and Applications.* Vol. 5, No. 3, 2017, pp. 15-21. doi: 10.11648/j.ajma.20170503.11

Received: April 22, 2017; **Accepted**: August 23, 2017; **Published**: September 23, 2017

Abstract: A crucible furnace is a piece of equipment used in the foundry industry for melting metals for casting operations. This research work focuses on the design of a 30-kilogram capacity aluminium crucible furnace that is fired with diesel fuel. The furnace drum has an overall combustion capacity of $0.1404m^3$. It is fitted with a chimney to allow for the easy escape of combustion gases. The air blower discharges air into the furnace at the rate of $0.3m^3/s$ with an air/fuel ratio of 400:1. The aluminium crucible furnace is designed to consume 4 litres of diesel fuel with a rating of 139000kJ/gallon which is required to completely melt 30-kilogram of aluminium over a period of 18 min. The designed operation temperature range of the aluminium crucible furnace is 500°C to 800°C. The cost of the aluminium crucible furnace is one hundred and eighty-two thousand nine hundred naira (N182, 900.00).

Keywords: Aluminium Metal, Crucible, Efficiency, Furnace, Melting Temperature

1. Introduction

Technological advancement of a nation depends solely on its capability to harness and convert its useful mineral resources into required finished products (Osarenwinda, 2015). In the processing of mineral resources such as metals, melting and extraction have become the critical industrial practices which are mostly carried out in a furnace. A furnace is equipment used to melt metals for casting or to heat materials to change their shape or properties (heat treatment) (Rajiv Garg, 2006; Furnace, 2015). Furnaces are usually classified according to the purpose for which the material is heated, nature of the transfer of heat to the material, method of firing the furnace and method of handling material through the furnace (Schlesinger *et al.,* 1998). They are refractory lined vessels that contain the material to be melted and provide the energy to melt it (Wikkipedia, 2015a). Based on the method of generating heat, furnaces are broadly classified into two types namely combustion type (using fuels) and electric type (Abed, 2013). The combustion type furnace can be broadly classified as oil fired, coal fired or gas fired (Wikkipedia, 2015b). Modern furnace types include electric arc furnaces (EAF), induction furnaces, cupolas, reverberatory, and crucible furnaces. Furnace choice is dependent on the alloy system and quantities produced. Most aluminum foundries use either an electric resistance or gas heated crucible furnaces or reverberatory furnaces. The oil fired crucible furnace uses the combustion of diesel as a fire source to heat the crucible and melt the solid metal inside it. Some of the advantages of oil fired crucible furnace are low investment costs, easy operation and maintenance ability, capable of melting small batches of various alloys, the melt can be treated directly in the crucible and the alloy can be quickly and easily replaced as necessary (Mastrukov, 1986). As important as oil fired crucible furnaces to the foundry and manufacturing process, its availability seem to be limited in Nigeria and when available most of them are imported and this is costing the country huge sum of foreign exchange.

Previous contributions on furnaces were described by Oyawale and Olawale (2011) in the development of a Mini-Electric Arc Furnace to melt 5kg of steel/cast iron scraps, using locally produced Soderberg electrodes. Performance evaluation on the furnace revealed that it required 60 minutes to heat up the furnace to the range of 1150°C – 1400°C.

Furthermore, about 95 minutes was required to melt the first charge of 2kg, resulting in a melting rate of 21.05g/minute. Alaneme and Olanrewaju (2010), also developed a diesel fired heat-treatment furnace using locally sourced materials which was targeted at disposing the use of heating elements requiring electric power which is poorly supplied in the country. Evaluation of the furnace was observed to have a fast heating rate of 61.24°C /min to attain a pre-set temperature of 900°C and a fuel consumption rate less than 1.41 litres/hr. According to Ramazan (2007), an electrical furnace with an automatic control to fire ceramic products was also developed. The aim of study was to develop a 30 Kg oil fired crucible furnace using locally sourced materials.

2. Materials and Method

2.1. Material Selection

The choice of materials for the development of the furnace was based on the following engineering requirements:

a) Weldability: This is the ability of the material to be welded
b) Toughness: This is the ability of the material to withstand shock and absorb energy due to impact.
c) Fatigue: This is the ability of the material to withstand cyclic stresses.
d) Ductility: This is the ability for the material to be drawn into wire.
e) Durability: This is the ability to stay strong and in good condition over a long period of time
f) Availability: This is the state of the material readily accessible.

The mild steel plate used for fabricating most components of the furnace is ductile, thus making it possible for it to be rolled, folded and bent without cracks or fractures.

The under listed materials were specified for the design of the diesel fired crucible furnace.

a) Mild steel plate (3mm)
b) 2 mm thick (ϕ 45) mild steel pipe
c) Gate Valve
d) Kaolin sand
e) Sodium silicate
f) Air blower
g) Flexible hose

The selected materials for the different components of the furnace are as stated in Table 1.

Table 1. *Material Selection Table.*

S/N	Furnace Component	Required Properties	Selected Material
1	Furnace unit	Ability to withstand internal pressure of 276MPa – 2070MPa.	5mm thick mild steel
2	Crucible pot	high heat resistance, high strength and good thermal conductivity	Cylindrical chromium based steel (3x225x205)mm
3	Cover	Ability to withstand internal pressure of 276MPa – 2070MPa.	3mm thick mild steel
4	Blower	light weight and ease of shaping	Aluminiumplate
5	Air pipe	resistant to corrosion and heat	mild steel
6	furnace insulator/ lining	good resistant to heat flow per unit thickness	refractory mixture of sodium silicate and kaolin using sawdust and water as binder
7	Fuel tank		2mm thick mild steel bucket

The furnace was fuel fired using diesel with slight kaolin in the combustion chamber.

2.2. Method of Construction

The 30kg aluminium crucible furnace was designed majorly to melt aluminium and other metals whose melting temperatures falls within its designed operation temperature range of 800°C below. Some of the equipment used in fabricating the various parts of the furnace are as follows: (a) Folding/rolling machine (b) Drilling machine (c) Welding machine (d) Cutting tools (e) Marking/Measuring tools etc.

The major components of the 30kg aluminium crucible furnace are as follows: (i) The Furnace Drum (ii) The furnace cover (iii) The Air Blower (iv) Fire bricks (v) Combustion chamber (vi) Furnace Cover Opening/Closing Mechanism.

2.2.1. Fabrication of the Furnace Drum

The furnace drum was made from a mild steel plate of 3mm thickness by folding the mild steel plate into a cylindrical shape of 800mm diameter with the aid of a rolling/folding machine. A circular mild steel plate of diameter 800mm was cut using a cutting machine and subsequently welded to the bottom of the folded drum with the aid of an arc welding machine.

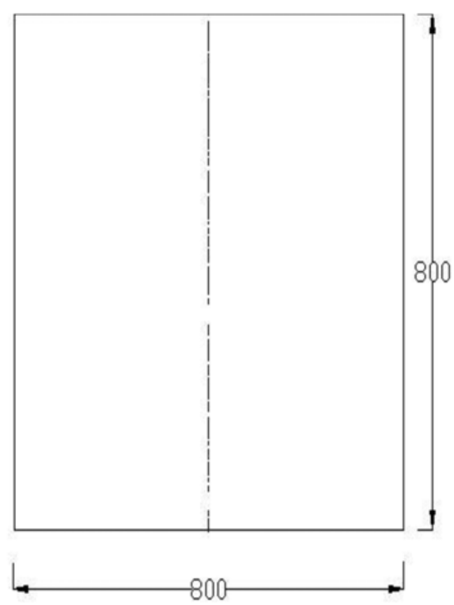

Figure 1. *Furnace Drum (All dimensions in mm).*

2.2.2. Fabrication of the Furnace Cover

The cover was made from a 3mm mild steel plate. The mild steel plate was cut with oxyacetylene flame and thereafter welded with an arc welding machine using gauge 12 electrodes. The cover was filled with a refractory mixture comprising of sodium silicate, kaolin, sawdust and water to prevent or reduce the amount of heat loss. 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.

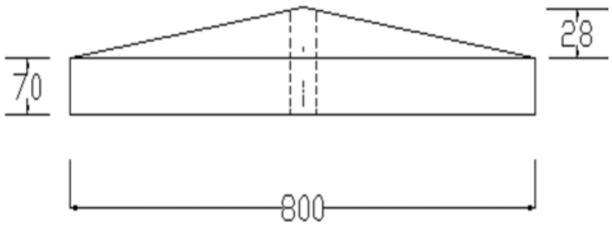

Figure 2. *Furnace Cover (All dimensions in mm).*

2.2.3. Lining the Furnace Wall with Bricks

The inner surface of the furnace drum was lined round with a double layer of bricks of about 230mm thickness using the refractory mixture comprising of sodium silicate, kaolin, sawdust 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 double layer of bricks of about 230mm thickness using the same mixture of kaolin, sodium silicate, sawdust with water as binder.

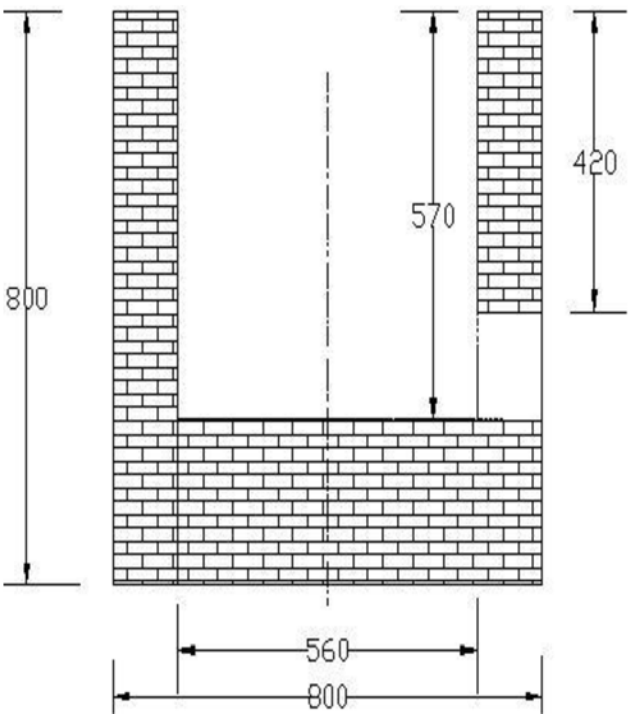

Figure 3. *Furnace Wall Linning (All dimensions in mm).*

2.2.4. Fabrication of the Combustion Chamber

This is the space under the crucible pot in the furnace unit meant for burning fuel in order to produce heat for the melting operation. It consists of the burner and its housing, designed to withstand high temperature and pressure developed during the process of combustion. To reduce loss of heat through the furnace walls, the inner and outer walls are separated using refractory materials made of sodium trioxosilicate coupled with kaolin sand. A blower is incorporated to provide sufficient air into the chamber for complete combustion of the fuel.

2.2.5. Fabrication of the Diesel Tank

The diesel tank was made from a mild steel plate of 2mm thickness. A rectangular shaped piece with dimensions of 800mm by 600mm were cut out of the mild steel plate with the aid of a cutting machine and thereafter welded together to form a cylindrical-shaped structure. Ahole 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

2.2.6. Assembling of Parts and Finished Operation

After all the parts were fabricated, the next step was coupling the furnace drum and cover. Thereafter, the combustion chamber was integrated into the furnace drum. The nozzle was at this point welded to the furnace drum. The air blower which was bought already made was subsequently connected to the nozzle. Lastly the pipe from the diesel fuel tank was linked to the furnace. The entire welded joints were deslagged and thereafter grinded/polished to ensure a smooth finish. Grinding was done with a hand grinding machine. After grinding a first stage painting of the outside body with antirust paint was done and was followed by a second stage and final painting with a black colored paint.

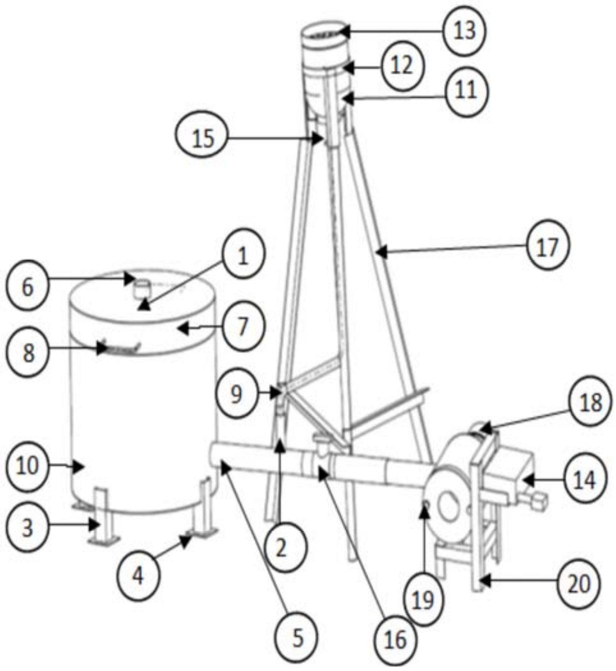

Figure 4. *Furnace Assembly Diagram.*

Table 2. *Part List of the Aluminium Crucible Furnace.*

S/N	Description	Quantity	Material
1	Cylinder Furnace cover	1	Mild Steel Plate
2	Fuel Inlet	1	Mild Steel Plate
3	Furnace Stand	4	Mild Steel Pipe
4	Furnace Stand base	4	Mild Steel Plate
5	Burner Assembly	1	Mild Steel Pipe
6	Chimney	1	Mild Steel pipe
7	Furnace cover	1	Mild Steel plate
8	Furnace Cover Handle	2	Mild Steel Rod
9	Fuel Hose	1	Rubber
10	Furnace wall	1	Mild Steel Plate
11	Fuel Tank	1	Mild Steel Plate
12	Fuel Tank Guide	1	Mild Steel
13	Fuel Sieve	1	Mild Steel Mesh
14	Power Control Box	1	Mild Steel Plate
15	Fuel Regulator	1	Brass
16	Air Regulator	1	Brass
17	Fuel Tank Stand	3	Angle Iron
18	Electric Motor	1	Modular
19	Bolts Head	6	Steel
20	Blower Stand	1	Angle Iron

3. Working Principle of the Crucible Furnace

The furnace is first and foremost preheated before firing it by igniting combustible materials such as coal in the combustible chamber. While the coal 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, thereby melting its content.

The furnace temperature can be read directly from a thermocouple inserted into the furnace through the cover. When the crucible content is fully melted and is ready for pouring, the crucible is lifted out by means of a lifting tong, which is handled by two persons and then poured into the prepared mould cavity. The holes on the sides of the furnace are made to keep a balance between the pressure within and outside the system.

3.1. Regulation of the Furnace Temperature

The temperature of the furnace was regulated by simply controlling the air/fuel mixture content. It is done by opening or closing slightly the control valves of either or both of air and diesel fuel, to regulate the air-fuel ratio or the amount of air and diesel fuel entering the combustion chamber. The furnace temperature was determined during melting operations by incorporation of a thermocouple in the furnace designed to enable the temperature of the metal during melting to be monitored.

Figure 5. *Temperature reading in progress.*

Figure 6. *Chimney for keeping pressure balance.*

Figure 7. *Molten Aluminum after melting.*

3.2. Design Analysis

3.2.1. Design Analysis of the Furnace Drum

The furnace drum was made from a 3mm thick mild steel plate rolled into a cylinder of diameter of 800mm and height 800mm with the overall combustion space of diameter 560mm and height 570mm.

The Detailed dimensions of the furnace drum are as follows:

a) Height of the furnace drum before laying bricks (h) = 800mm
b) Height of combustible space of the furnace drum after laying of bricks (h_1) = 570mm
c) Internal diameter of the furnace drum before laying of bricks (d) = 790mm
d) Internal diameter of the furnace drum after laying of bricks (d_1) = 560mm
e) Inlet diameter of the burner nozzle = 102mm
f) Outlet diameter of the burner nozzle = 35mm
g) Height of the cover = 98mm
h) Total height of the drum = height of drum + height of cover = 800 + 98 = 898mm.
i) Diameter of the chimney hole (on cover) = 60mm
j) Thickness of the metal plate = 3mm

Therefore Combustible Volume of furnace after laying of bricks:

$$V_1 = \frac{\pi d_1^2 h_1}{4} = \frac{3.142x560^2x570}{4} = 140409696\text{mm}^3 = 0.1404\text{m}^3 \quad (1)$$

3.2.2. Design Analysis of the Air Blower

The air blower is rated as follows;
Outlet pressure = 1700Pa, (from blower)
Speed = 2850 rpm
Power = 0.55 KW
Voltage = 220 V
Current = 2.5 Amperes
Average rate of air flow from blower = 18m^3/min
Average rate of fuel flow = 0.045m^3/min

$$\text{Ratio of air discharge to fuel discharge} = 18/0.45 = 400:1 \quad (2)$$

4. Performance Evaluation of the Furnace

The furnace was fired and the time taken to raise the temperature to 660°C was 15 minutes. Thereafter, the 30 kg of aluminium scrap was placed in it. A holding time of 18 minutes was required to completely melt the aluminium batch. The furnace design temperatures are as follow:

a) The ambient temperature, T_a = 15°C
b) The melting temperature of the aluminium, T_m = 660°C
c) Furnace Maximum Design Temperature = 800°C

The transient time-temperature result gotten from the experiment is as shown in table 2.

Table 3. *Furnace time-temperature result.*

Time (min)	Temperature attained (°C)	Heating Rate (°C/min)
3	126	42.00
6	270	45.00
9	401	44.56
12	520	43.33
15	660	44.00
18	780	43.33

Table 4. *Table Symbols.*

S/N	Symbol	Definition	Standard Unit
1	ϕ	Diameter	m
2	h	Height	m
3	T_a	Ambient Temperature	° C
4	T_m	Melting Temperature	° C
5	Δθ	Difference in temperature	° C
6	m	Mass of the material	Kg
7	Cp	Specific Heat capacity	KJ/Kg. K
8	L	Specific latent heat of vapourization	KJ/Kg

$$Efficiency = \frac{heat\ required\ to\ melt\ the\ aluminium}{heat\ used\ to\ melt\ the\ aluminium} \times 100 \quad (3)$$

$$Efficiency = \frac{Heatenergy_{theoretical}}{Heatenergy_{experimental}} x100 \quad (4)$$

The efficiency of the crucible furnace when melting aluminium is calculated as follows:

Mass of the Metal (Aluminium) = 30Kg

Specific Heat Capacity of Aluminium (solid) = 0.91KJ/Kg.K

Specific Heat Capacity of Aluminium (molten) = 1.18KJ/Kg.K

Latent Heat of Fusion of Aluminium = 321KJ/Kg

Melting Point of Aluminium = 660°C

The theoretical energy content to melt 30Kg of aluminium metal at 660°C when assume its initial temperature at standard temperature and pressure of 15°C is calculated below:

$$\text{Temperature rise to melting point } (\Delta\theta) = 660\text{-}15 = 645°\text{C} \quad (5)$$

Energy content required to raise temperature of metal to melting point:

$$mC_p\Delta\theta = 30 \text{ x } 0.91 \text{ x } 645 = 17,608.5 \text{ KJ} \quad (6)$$

Energy content required to superheat to 780°C = 30 x 1.18 x (780-660) = 4,248 KJ (7)

Energy content required to change metal from solid to liquid

$$mL = 30 \text{ x } 321 = 9,630 \text{ KJ} \quad (8)$$

Total energy content of Aluminium = 17,608.5 + 4,248 + 9,6 30 = 31,486.5 KJ (9)

The total amount of energy consumed in the furnace is calculated by multiplying the number of litres of fuel by the energy content per litres of fuel used.

Energy content of fuel is rated 139000 KJ/gallon (1 gallon = 4. 6 Litres) British Standard

Therefore, energy content of the fuel is $\frac{13900}{4.6} = 30217.39KJ$ (10)

4 litres of fuel was used to melt the 30 Kg mass of aluminium

Therefore, total amount of energy used by the furnace = 4 x 3 0, 217. 39 = 120, 869.56 kJ (11)

$$Efficiency = \frac{Heatenergy_{theoretical}}{Heatenergy_{experimental}} x100 = \frac{31486.5}{120869} x100 = 26.5\% \quad (12)$$

4.1. Discussion of Results

From the results obtained above, the efficiency of the furnace was calculated to be 26.5%, which falls within the efficiency range of conventional furnace, showing that most of the heat generated in the furnace was actually used in the melting of the metal.

A crucible furnace of 30kg melting capacity has been designed in line with the set objective of the research work. When compared with the efficiency of 25% obtainable from the conventional crucible furnace, it can be said to be over 80% efficient as well as effective, and can conveniently replace the conventional imported crucible furnace in line with the Federal Government import substitution policy in order to conserve foreign exchange. Moreover, with design temperature range of 500°C to 800°C, aluminium can be conveniently melted using the 30kg melting furnace.

4.2. Safety Precaution

There must not be any leakage in fuel along the length of the hose carrying fuel to the combustion chamber. After the melting has been completed, the gate valve that is releasing fuel to the combustion chamber should be tightly locked. All these are meant to avoid fire explosion.

4.3. Bill of Engineering Measurement and Evaluation

Table 5. *Summary of BEME.*

S/N	Description of Materials	Qty	Unit Price (N)	Total
1	3mm mild steel sheet	1	10000	10000
2	2mm Mild Steel Plate	1	7000	7000
3	Gate Valves	2	1500	3000
4	Electrode (guage 12)	2 packets	1200	2400
5	Crucible pot	1	10000	10000
6	Refractory bricks	80	300	24000
7	Kaolin and Sodium Silicate	Bulk	12000	12000
8	Angular Bar (2x2), RSJ (4X2) (Half Length)	1	13500	13500
9	5" Mild Steel Pipe (Full Length)	1	10000	10000
10	Flexible Hose	5m	200	1000
11	Air Blower with motor	1	20000	20000
12	Thermocouple with Indicator	1	30000	30000
12	Labour			10000
13	Miscellaneous/Transport of Materials		10000	10000
14	Detail Cad Drawing &Eng Design of Components			20000
	TOTAL			182900

5. Conclusion

In this project, a crucible furnace was developed with the capacity to reach a temperature of 780°C within 18minutes, thereby producing heat of 120,869.56KJ. The production cost of the furnace was N182, 900 (One hundred and eighty two thousand, nine hundred naira). It has a melting efficiency of 20%, and thus should be able to contribute to the development of small scale foundry businesses in Nigeria.

References

[1] Abed E. J., (2013). Manufacture and Performance of Gas Furnace. International Journal of Metallurgical Materials Science and Engineering. Vol. 3, Issues 1, Pg 109-118

[2] Alaneme K. K., and Olanrewaju S. O., (2010). Design and Construction of a Diesel Fired Heat-Treatment Furnace. Journal of Minerals & Materials Characterization & Engineering. 9(7), Pg 2581-591.

[3] Furnace (2015). www.materialrulz.weebly.com/furnacesuploads.pdf

[4] Mastrukov B. C., (1986). Design of Metallurgical Furnaces. Moscow: Metallurgical publication.

[5] Osarenmwinda J. O., (2015). Fabrication and Performance Evaluation of Oil-Fired Crucible Furnace using locally sourced materials. International Journal of Engineering Research and Applications. Vol. 5, Issue 3, Pg 29-33.

[6] Oyawale F. A and Olawale D. O., (2011). Design and Prototype Construction of a Mini-Electric Arc Furnace. The Pacific Journal of Science and Technology 8(1)Pg 12-16.

[7] Rajiv Garg (2006). Thermal Energy Equipment: Furnaces and Refractory. Energy Efficiency Guide for Industry in Asia.

[8] Ramazan B., (2007). Design and Construction of an Electrical Furnace to Fire Ceramic Product. Journal of Scientific and Industrial Research Vol. 66, Pg 135-140.

[9] Schlesinger M. D., Baczewski, K. C. and Baggley, G. W., (1998). Fuels and Furnaces.

[10] Wikkipedia (2015)a. http://en.wikipedia.org/wiki/Foundry.

[11] Wikkipedia (2015)b. Types and Classification of Different Furnace. www.productivity.in.