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Determining Thermal Characteristics of an Oil-Fired Crucible Furnace Using Clay and Alumina Bricks

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Abstract: *This paper explores the results of an experimental study that was intended to determine the thermal characteristics of an oil-fired crucible furnace using clay and alumina bricks. For the study, a refractory with 0.03118m^3 combustion chamber capacity was used. The bricks analysis were carried out under transient condition that would be appropriate for laboratory and workshop with a capacity to reach 950ºC within 20 minutes for aluminum and nonferrous scrap re-melting. The performance of the furnace was evaluated, and the results showed that the furnace can operate at a heating rate of 49.44°C/min, with a 29.70% efficiency determined, and which was within the efficiency range of conventional furnace. The heat transfer coefficient of 4.48W/m^{2}K was obtained. Alumina bricks used in lining the furnace was attributable to its higher refractoriness. It was found that a better thermal shock was proved than clay bricks from the Comparative analysis simulation using commercial software ANSYS 14.0 aimed towards improving service life and efficiency.*

Keywords: *Aluminum, Secondary smelting, Refractory Bricks, crucible furnace, thermal efficiency, heat transfer coefficient*

1. Introduction

Aluminum is a renewable resource that has endless opportunities for generations to come (Osoba et al., 2018). Aluminum alloy manufactured components is well used in aerospace, automotive, packaging, offshore and marine constructions as it offers light weight, good corrosion resistance and excellent formability (Klauber et al., 2011; EAA, 2004). Aluminum and its alloy can be produced through primary and secondary smelting processes. Secondary aluminum often involve recycling aluminum scrap as the energy required for this process is ~5% of that required for primary aluminum production while yielding comparable quality aluminum as primary smelting (Das et al., 2007; Mukhopadhyay et al., 2005). One of the means by which secondary smelting of aluminum could be performed is through the use of crucible furnace that may be open or close. In the early nineteenth century, the phenomenon of crucible furnace was applied to the experimental melting of non-ferrous metals. However, the previously used crucible furnaces in local foundries are associated with the many problems namely: full exposure to heat and combustible products which are harmful to the body and health, loss of heat due to the open nature of the local furnace, which leads to prolonged operational activities with undesired result.

Based on the method of generating heat, furnaces are broadly classified into two types, namely combustion type (using fuels) and electric type. Based on the kind of combustion, it can be broadly classified as oil fired, coal fired or gas fired (Mehta et al., 2013). The majority of the heat loss i.e. around 40% of heat input is flue gas loss and only an estimated 10% of available heat is lost through the refractory wall during steady state operating conditions (Whipple, 2008; Owolabi et al 2016). Furnaces vary in design, geometry, production capacity (melting rate), materials of construction, and mode of operation (Daviess, 1970). One of the major challenge in design optimisation of the aluminum recycling process is numerical modelling of the furnace (Khoei et al., 1999; Khoei, 2000., Khoei et al 2002) in which this paper uses Ansys 14.0 to simulate the refractory bricks used for lining the furnace.

Ekpe et al. (2015) designed and fabricated an Aluminum Melting Furnace. Butane gas was used as the thermal energy source in heating up the system to the melting point of aluminum (660.4°C). Results showed great reduction in energy consumption and improved furnace efficiency of 28%. Many other researchers have worked on enhancing the performance evaluation of oil fired crucible furnace for melting al scrap, among others are Olukokun et al. (2019) with efficiency of 10.8%, Osarenmwinda (2015) with an improved furnace efficiency of 10.34%, Ighodalo et al. (2015) with a furnace efficiency of 11.5%, Adefemi et al. (2017) with an efficiency of 26.5%.

Furnace designs are made of different parts of different materials. The materials expand as temperature increases and contract as it decreases. This can lead to thermal fatigue causing cracking of the fuel fired crucible furnace linings. In practice, however, a lot of heat is lost in several ways, namely: energy conversion losses, furnace wall losses, furnace opening losses and the likes (Gilchrist, 1997; Holman, 1974; Trinks, 1967). The complexity of the phenomena that occur in real conditions makes it difficult to analyse accurately the study where conduction, convection and radiation occur concurrently on refractories used for furnace lining (Song et al., 1991).

Hence, the use of commercial software (Ansys, 14.0) can help get accurate result for the thermal analysis on the refractories used. Also the occurrence of high rate of fuel consumption and uncontrolled heat loss often limit the efficiency of crucible furnaces. Therefore, optimisation of these furnaces is of great importance to improve its performance (efficiency) during aluminum smelting for customised design of fuel fired crucible furnace. This current study presents the thermal characteristics evaluation results of an oil (diesel) fired furnace for the smelting of aluminum alloy. To minimise these losses, materials that can retain and conserve heat known as refractory materials can be used as lining materials in furnaces.

2. Methodology

2.1 Materials and Methodology

The following materials were specified for the design of the diesel fired crucible furnace: mild steel plate (3mm), 2 mm thick (ϕ 45) mild steel pipe gate valve, kaolin sand, refractory cement (durax) and flexible hose. Composition of the mild steel is shown in Table 1.

2.2 Method of Construction

The 10kg aluminum crucible furnace was designed majorly to melt aluminum and other nonferrous metals whose melting temperatures falls within its designed maximum operation temperature of 900°C. The major components of the 10 kg aluminum crucible furnace are: (i) furnace drum, (ii) furnace covers, (iii) air blower, (iv) fire bricks, (v) combustion chamber, and (vi) furnace cover opening/closing.

Hence, the design criteria are:

1. The furnace must be large enough to represent actual, working furnaces.
2. The furnace must be small enough that it would be useful as a research tool.
3. The furnace must be modular in nature.
4. The furnace must be able to be equipped with off-the-shelf facility and any custom equipment designed through the course of the project.

2.3 Major Features of the Furnace

The furnace component and material selection criteria are given in Table 2, and the bill of engineering measurement and evaluation as shown in Table 3.

Table 1. Compositional Analysis Result of Mild Steel Plate (MS)

C	Si	Mn	P	S	Cr	Mb	Ni	Al	Cu	Zn	Fe	V
0.2267	0.2361	0.0412	0.0412	0.0616	0.1343	0.0212	0.1014	0.0025	0.2588	0.0059	98.095	0.0027

Table 2. Material Selection Table

S/N	Furnace Component	Required Properties	Selected Material
1	Furnace unit	Ability to withstand internal pressure of 276 MPa – 2070 MPa	3 mm thick mild steel
2	Crucible pot	High heat resistance, high strength and good thermal conductivity	Graphite and silicon carbide
3	Cover	Ability to withstand internal pressure of 276 MPa – 2070 MPa	3 mm thick mild steel
4	Blower	Light weight and ease of shaping	Aluminum 220V, 1.6A, 50/60Hz
5	Air pipe	Resistant to corrosion and heat	Mild steel
6	Furnace insulator/ lining	Good resistant to heat flow per unit thickness, with high thermal conductivity	Refractory mixture of Durax, and water
7	Fuel tank		2 mm thick mild steel bucket

Table 3. Bill of Engineering Measurement and Evaluation

S/N	Material description	Unit	Quantity	Unit cost ₦	Total cost ₦	Dollar Equivalent ($)
1	5 x 65 x 65 angle bar	2.4 cm	2	2,300	4,600	12.70
2	Furnace drum		1	12,000	12,000	33.20
3	Fuel tank		1	2,000	2,000	5.53
4	Tap or valve		1	500	500	1.38
5	Rubber tubing		1	3,000	3,000	8.29
6	Clips		10	200	2,000	5.52
7	Meter rule	mm	4	100	400	1.10
8	230 x 115 x 65 brick		30	1,000	30,000	83.00
9	Diesel fuel	litre	2	200	400	1.00
10	Bolt and nut		10	100	1,000	2.80
11	Blower		1	35,000	35,000	97.00
12	Galvanized pipe	800 mm Length	1	4,600	4,600	13.00
13	Kaoline clay	kg	1	3,000	3,000	8.30

Table 3. *(Continued)*

S/N	Material Descriptions	Unit	Quantity	Unit cost ₦	Total cost ₦	Dollar Equivalent ($)*
14	Water	20 litre gallon	3	10	30	0.08
15	Cutting Disc	4.5 inches	3	1,500	4,500	12.50
16	Guage12 electrode	Packet	2	1,800	3,600	10.00
17	Crucible pot		1	35,000	35,000	97.00
18	Plank	Length	1	1,600	1,600	4.40
19	Calcium aluminate cement (Durax 1600)		2	15,000	30,000	83.00
20	Pyrometer		1	35,000	35,000	97.00
21	Transportation/Miscellaneous			15,000	15000	41.50
22	Total overall cost				₦223,230	616.00

* - Remarks: Exchange rate ₦/$=362

2.4 Modelling of Refractory Bricks

Three dimensional model of a refractory brick is represented in Figure 1. The bricks were modelled using Solid Works software. Thereafter, the model was imported into ANYS workbench 14.0 for analysis. Thermal properties were built in the engineering data software for the varied bricks (see Table 4). The set up for the analysis was done with a finite element mesh on the model. While in the Model, the configured thermal properties were assigned to the geometry, and varied properties were examined at a temperature of 750°C. The set mesh of the refractory bricks has statistics of nodes and elements 28,807 and 6,300, respectively (see Figure 2).

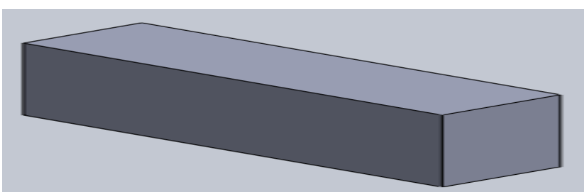


Figure 1. 3-D Model of the Crucible Brick

Table 4. Thermal Properties of Clay Bricks and Alumina Refractory

Material properties	Clay Bricks	Alumina
Density	2100kg/m^3	3980 kg/m^3
Melting	1230°C	2100°C
Maximum service temperature	927°C	1300°C
Thermal conductivity	0.73W/m°C	38.5W/m° C
Specific heat capacity	850J/kg°C	820J/kg° C
Thermal expansion coefficient	8*10^{-6} Strain/°C	7.9*10^{-6} Strain/°C

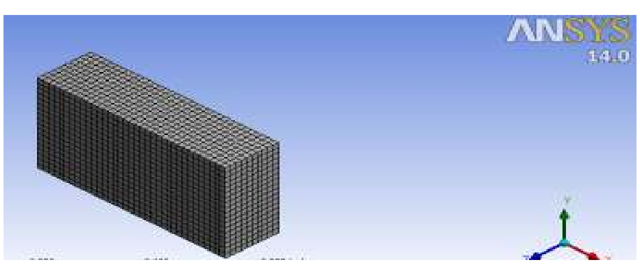


Figure 2. Finite Element Mesh of the Bricks

3. Results and Discussion

3.1 Comparative Analysis of Refractory Bricks

From the transient thermal analysis result, it was observed that the maximum heat flux of clay bricks (see Figure 5) and Alumina bricks (see Figure 3) is 4.750*105 W/m^2 and 5.2394*10^6 W/m^2, respectively, and the maximum directional heat flux of clay bricks (see Figure 6), and alumina (see Figure 4) were found to be 3.7723*10^{5}W/m^2 5.2394*10^6 W/m^2, respectively. Comparatively, it was observed that, thermal loading was high in clay bricks.

This is as a result of higher specific heat capacity and thermal expansion coefficient of alumina refractory (Xin, 2013; Lee, 2000). Thus, the refractory lining of the furnace under transient conditions should have excellent thermal shock properties i.e., volume stable, high thermal conductivity, and low thermal expansion (Nandy and Jogai, 2012). Hence, alumina will exhibit low thermal load and thermal shock which will enhance the durability and suitable for the lining of the wall of the crucible furnace for non-ferrous metal application.

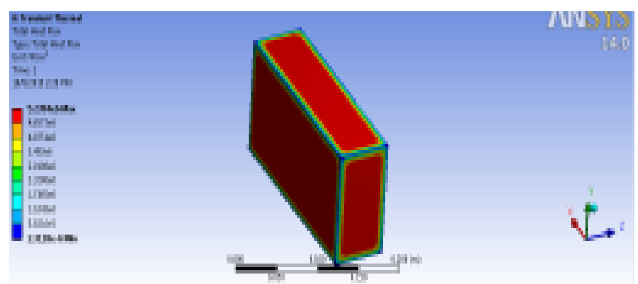
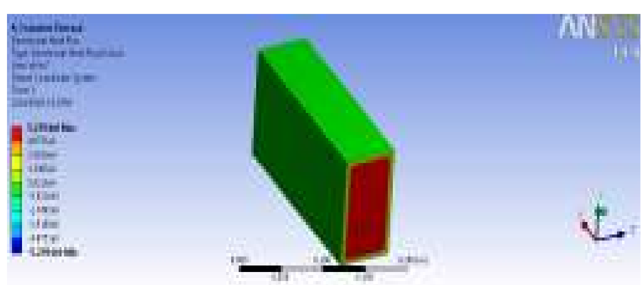


Figure 3. Total Heat Flux of Alumina Brick



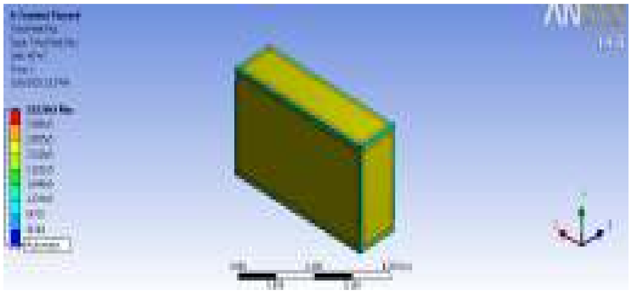


Figure 5. Total Heat Flux of Clay Bricks

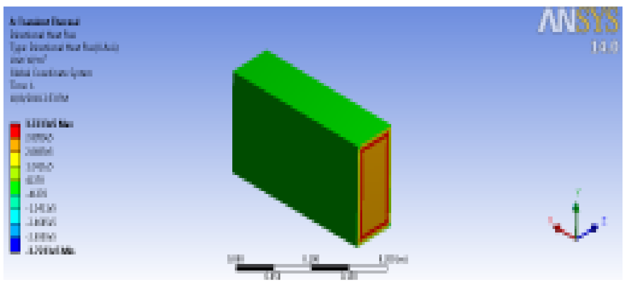


Figure 6. Directional Heat Flux of Clay Bricks

3.2 Design Analysis

The aluminum melting furnace was evaluated to ascertain its performance by melting aluminum scraps at a temperature of 660 °C (933K). Preheating was done in the first 10 minutes to enhance good heat distribution in the combustion chamber. The results obtained were tabulated as indicated in Table 5. The efficiency of the furnace was calculated to be 29.70%, which falls within the efficiency range of conventional furnace, showing that most of the heat generated in the furnace was used in the melting of the metal.

Solid works 2014 was used for the 3D model and Wire frame model as seen in Figures 7 and 8, to show the skeletal view of the customised crucible furnace. The furnace drum was made from a 3 mm thick mild steel plate rolled into a cylinder of diameter of 510 mm and height 470 mm with the overall combustion space of diameter 495 mm and height 320mm.

Detailed dimensions of the furnace drum are as follows:

a) Height of the furnace drum before laying bricks (h) = 470 mm
b) Height of combustible space of the furnace drum after laying of bricks (h_1) = 405 mm
c) Internal diameter of the furnace drum before laying of bricks (d) =510 mm
d) Internal diameter of the furnace drum after laying of bricks (d_1) = 495 mm
e) Inlet diameter of the burner nozzle = 30mm
f) Outlet diameter of the burner nozzle = 40mm
g) Height of the cover = 120 mm
h) Total height of the drum = Height of drum + height of cover = 470 + 120 = 590 mm.
i) Diameter of the chimney hole (on cover) = 100 mm
j) Thickness of the metal plate = 3 mm
k) Total height of the crucible furnace = 470+120 = 590 mm
l) Height of the crucible body = 170 mm
m) Thickness of the crucible = 10 mm
n) Diameter of the crucible = 150 mm
o) Thickness of the Durax lining = 50 mm
p) Height of furnace cover = 120 mm
q) Diameter of furnace cover = 510 mm

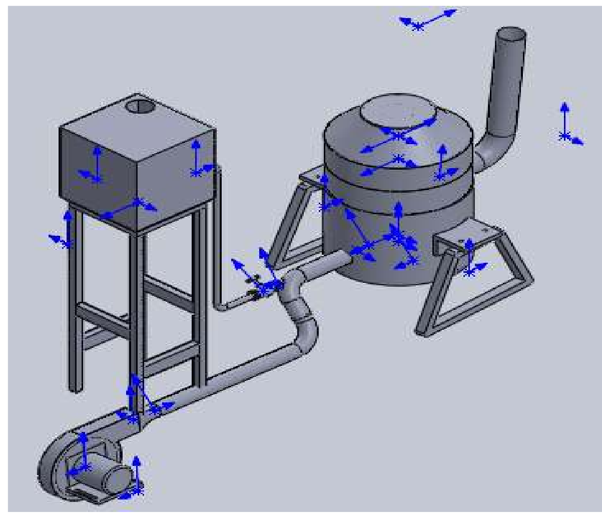


Figure 7. 3-D Model of the Furnace

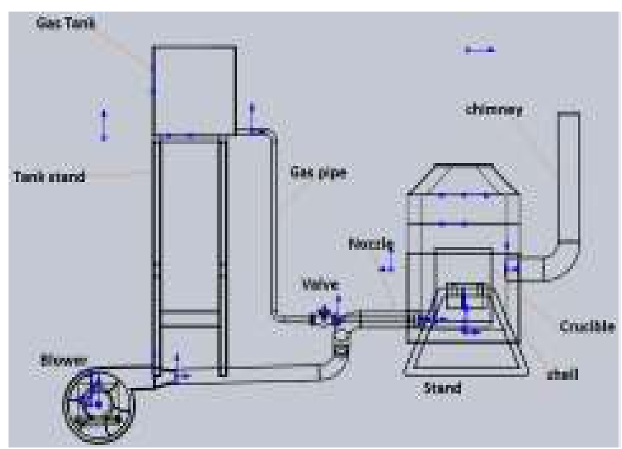


Figure 8. Wire Frame of the Furnace Assembly

Volume of combustion chamber (Combustible Volume of furnace after laying of bricks):

$$V_1 = \frac{\pi D_1^2 H_1}{4} \quad (1)$$

$$V_1 = (3.142 \times 405 \times 495^2) / 4$$
$$= 311796762.75 mm^3$$
$$= 0.3118 m^3$$

Table 5. Transient Time-temperature Result during Pre-heating and Actual Melting

Time (min)	Temperature(ºC)	Heating Rate (ºC/min)
0	25	
5	150	30
10	400	40
0	400	
10	500	50
15	740	49.33
20	980	49.0
Average		49.44

3.3 Efficiency of the Oil-fired Crucible Furnace

Heat energy Q_1, needed to raise the temperature of the metal from room temperature to the melting point of the metal, determined as: $Q_1 = Mc_{p1} (T_m - T_A)$ (Sinha and Goel 1973). According to Suresh and Nagarium (2016), specific heat capacity of aluminum (solid) is 0.91KJ/Kg.K. Hence, based on Kothandaraman and Subramanyan (2014), specific heat capacity of aluminum (molten) is 1.18KJ/Kg.K. Given other parameters below:

Latent Heat of Fusion of Aluminum = 321KJ/Kg
Melting Point of Aluminum = 660°C
Ambient temperature T_A =25ºC
Mass of Aluminum melted = 5kg

$$Q_1 = Mc_{p1}(T_m - T_A) \quad (2)$$
$$= 5 \times 0.91 \times 10^3 (933 - 298)$$
$$= 2889.25KJ$$

Energy Q_2 needed to raise the temperature of the metal from room temperature to the melting point of the metal (Sinha and Goel, 1973).

$$Q_2 = mL \quad (3)$$
$$= 5 \times 321 = 1605\text{KJ}$$

Energy Q_3 (super heat) required to raise the temperature of molten metal from its melting point to the required pouring temperature (750ºC) (Sinha and Goel, 1973).
It is given as:

$$Q_3 = Mc_{p2} (T_p - T_m) \quad (4)$$
$$= 5 \times 1.18 \times (1023 - 933)$$
$$= 531\ KJ$$

Heat required for a melt, Hear output, Q_n

$$Q_n = Q_1 + Q_2 + Q_3$$
$$= Mc_{p1} (T_m - T_A) + mL + Mc_{p2} (T_p - T_m) \quad (5)$$

Total energy required by aluminum

$$Q_n = 288925 + 1605 + 531 = 5025.25\ KJ$$

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). Therefore, energy content of the fuel is

$$139000/4.6 = 30217.39KJ$$

0.58 liters of fuel was used to melt the 5Kg mass of aluminum. Therefore, total amount of energy used by the furnace = 0.56 x 30,217. 39 = 16921.74*KJ*

Theoretical thermal efficiency of the furnace is given by

$$\eta = \frac{\text{Heat output of the furnace}}{\text{Heat supplied by the fuel}} \times 100\% \quad (6)$$
$$= 5025.25 / 16921.74 \times 100\%$$
$$= 29.70\%$$

From Newton's law of cooling equation;

$$Q/A = hc\ \Delta T \quad (7)$$

where,
Q = heat flow rate
A = area of cylinder
h_c= heat transfer coefficient
ΔT = temperature difference across wall

The heat output is calculated as follows

$$Q = Mc_{p1} (T_p - T_A)$$
$$= 5 \times 0.91 \times 10^3 (1023 - 298) = 4540.9KJ$$

$$\text{Area of cylinder} = 2\pi r (H + r) \quad (8)$$
$$= 2 \times 3.142 \times 247.5 (405 + 247.5)$$
$$= 1555.29(652.5) = 1014826.725mm^2 = 1.015m^2$$

$$\Delta T = 1023 - 298 = 998K$$

Substituting

$$h_c = Q / A\ \Delta T$$
$$= 4540.9 / (1.015 \times 998) = 4.48 W/m^2K$$

The results in Table 5 show that the melting furnace can achieve its main objective of recycling laboratory sie aluminum (5 Kg) in a single operation. A significant improvement in efficiency (29.70%) was recorded compare to 4-6 % in using the traditional furnace (Ilori, 1991) and 28% efficiency from Ekpe et al. (2015) due to the use of better refractories (Alumina bricks and refractory cement) It also takes a shorter time to melt the aluminum because of the improved heating rate of furnace at 49.44ºC/min, which will aid great reduction in the energy consumption .Calculated heat transfer coefficient is higher compare to that obtained by Ekpe et al. (2015).

The developed furnace will not only melt Aluminum but also any metal that has melting temperature below 1500°C. When compared with the efficiency of 25% obtainable from the conventional crucible furnace (Bureau of energy efficiency, 2019).

4. Conclusion

The designed and developed oil-fired crucible furnace was used to melt aluminum scraps and the following inference are made:

1. The crucible furnace proved to be effective for melting of aluminum and other aluminum alloy
2. Selection of appropriate refractories during fabrication enhances the efficiency and productivity of furnaces
3. The locally designed and developed furnace is comparatively economical and time saving during operation compared to investigated furnace in literatures

4. The device is suitable for use in small scale foundries and tertiary institutions, and
5. The locally designed and developed furnace is recommended for use in small scale foundries and tertiary institutions laboratory and workshop.

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