DEVELOPMENT OF A 5KG CAPACITY INDUCTION FURNACE FOR MELTING ALUMINIUM

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ABSTRACT

Aluminium 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 aluminium in all aspects of human endeavour which gives the country abundance of secondary raw material for aluminium production. Most of the furnaces available are either fuel by fossil fuel or are large or expensive. A5kg induction furnace has been developed for melting aluminium. The furnace is designed and fabricated using local materials for small scale production. The heating process is fundamentally based on electromagnetic means and the graphite was selected as the crucible material. A temperature of 775 ^{O}C was achieved in 8 minutes for the furnace which is satisfactory as it is higher than the melting temperature of aluminium (660.4 ^{O}C). Therefore, this fabricated induction furnace can be encouraged to be used in our local foundries, companies and institutions in Nigeria and overseas as a medium for learning, faster production and to encourage local production.

Keywords: *Aluminium, aluminium scraps, crucible, induction furnace, melting temperature.*

1. Introduction

Aluminium is a metallic element that has numerous uses especially in Nigeria, it is used in transportation, machine components and even in cooking utensils. It is used to primarily used to produce pistons, engine and body parts for cars, beverage cans, door and window (frames), bars wires and also for aircraft components (Ekpe et al., 2016).

Aluminium is primarily produced from bauxite ore. Bauxite is a rock formed from a reddish clay material called laterite soil and is most commonly found in tropical or subtropical regions. Bauxite is primarily comprised of aluminium oxide compounds (alumina), silica, iron oxides and titanium dioxide. Approximately 70 % of the world's bauxite production is refined through the Bayer chemical process into alumina. Alumina is then refined into pure aluminium metal (Ekpe et al., 2016).

However, the element is rarely available as rich ores, which leads to countries relying on its importation to satisfy demand (Bala, 2005). Another method of obtaining Aluminium is through secondary production, i.e., recycling. This method according to Ekpe et al. (2016) saves up to 95 % of energy compared to the primary refinement from ore and is also cheaper.

An induction furnace is an electrical furnace where heat energy is transferred directly from the induction coil into the metal to be melted without having contact directly with the metal through the electromagnetic field produced by the induction coil. The emphasis on secondary aluminium processing has caused increase in the development of furnaces for aluminium processing. Most of the furnaces available are either fuel by fossil fuel or are large or expensive, hence the need for developing a small-scale furnace that is made from locally available materials and cheap. The paper is aimed at presenting a developed 5kg induction furnace for melting aluminium and is also introducing a small size model of furnace for our institutions, enrichment of knowledge, technical skill, small scale production of metals in a short-limited time range and also empower the student to be self-employed.

2. Literature review

Historically, the early development of induction furnace started as far back as Michael Faraday, who discovered the principle of electromagnetic induction. However, it was not until the late 1870's when De Ferranti, began experiments on Induction furnaces in Europe. In 1890, Edward Allen Colby patented an induction furnace for melting metals and produced his first steel in the United States in 1907 (Anaidhuno and Mgbenuna, 2015). The first practical usage was in Gysinnge, Sweden, by Kjellin in 1900 and was similar to the Colby furnace. In Germany 1906 the first induction furnace for three phase application was built by Rochling - Rodenhauser. During World War II, the technology grew rapidly to satisfy pressing wartime demands for a quick and authentic method of hardening metal engine parts (Anaidhuno and Mgbenuna, 2015).

The huge economic benefit of the secondary method aluminium production has enabled the continued interest in developing various furnaces for its processing. Bhandari et al. (2018) designed a Crucible Furnaces by using Black Smithy Setup. The furnace was constructed in pit format with fire bricks of 75 mm thickness and a dimension of 220 × 110 mm. The time taken to melt aluminum is 75 minutes and ambient temperature was 30°C, maximum furnace temperature achieved was 1000 °C.

Adeodu et al. (2017) developed of a 30 Kg aluminium diesel-fired crucible furnace using locally sourced materials. The furnace drum had a combustion capacity of 0.1404 m^3 and fitted with a chimney to allow for combustion gas escape. A blower was incorporated in the system, it was designed to discharge air into the furnace at the rate of 0.3 m^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 139000 kJ/gallon which is required to completely melt 30-kilogram of aluminium over a period of 18 min. the furnace was able to reach a temperature of 780 ^{O}C in 18 minutes.

Bhamare et al. (2017) fabricated a Portable Metal Melting Furnace. The heating medium is LPG gas. The components selected for the manufacturing were metallic plate, insulating material (glass wool), burner, gas cylinder, gas pipe, LPG gas, graphite crucible and gas regulator. The gas cylinder of 5 kg was used with a 1.0 kg/hr regulator. A maximum of 680 ^{O}C was reached by the furnace in 15 minutes.

Meriga et al. (2018) developed a low-cost electrical resistance-based metal melting furnace for casting applications. The furnace was designed to melt metals with temperatures below 1000 ^{O}C. It was tested with aluminium and its alloys and a 700 ^{O}C was achieved in 100 minutes. The charge inserted took 100 minutes to melt.

3. Methodology

The design was considered in two (2) phases; the geometrical and the electrical considerations of the furnace. The crucible used in this project is graphite and other materials are locally available most especially the charge material (aluminium) which can be found littered in our environment, these will help reduce used aluminium and recycle them for other purposes. The heating process is fundamentally based on electromagnetic means, the energy from a coil through which a current flow whereby circulating through the heating coil. The method of fabrication was achieved by cutting with manual hacksaw, drilling with hand drill and joining with electric arc welding machine.

3.1 Design Analysis of the Induction Furnace

3.1.1 Volume of the metal charge intended

The design analysis is based on a 5kg capacity and the shape of the crucible is cylindrical. The volume of the metal charge intended is determined using Equation (1).

$$V_m = \frac{\pi d_m^2 H_m}{4} \qquad (1)$$

Where, d_m is the diameter the molten metal will occupy and H_m is the height to be occupied in both in m, with values of 0.07 and 0.13 m respectively.

3.1.2 The thickness of refractory lining

The thickness of the refractory lining of the crucible in the middle of the crucible was determined from Equation (2) according to Bala (2005).

$$B_r = 0.084\sqrt{T} \quad (2)$$

Where, T is the furnace capacity in tonnes. The furnace capacity is 5Kg in Tonnes is equal to 0.005 t, it is obtained as $B_r = 5.94$ mm.

3.1.3 The Height of Furnace from Bottom of the Bath to the Pouring Spout

The height of furnace from bottom of the bath to the pouring spout is given by Equation (3) (Bala, 2005).

$$H_f = (H_m + H_s + b_t) \quad (3)$$

Where, H_s is the height of slag formed in m, b_t is the thickness of bottom refractory lining and is b_t = 25.5 mm for 5kg capacity (Meriga et al., 2018).

The slag height, H_s was calculated using Equation (4) as given by Bala (2005).

$$h_s = \frac{4V_s}{\pi d_m^2} \quad (4)$$

V_s is the volume of slag in one heat, taken as 8% of total charge in m^3. H_f was obtained as 165.89 mm.

3.1.4 Internal Diameter of the Inductor

The internal diameter of the inductor, D_{in} was calculated as 93.88 mm from Equation (5) as stated by Meriga et al. (2018).

$$D_{in} = d_m + 2(B_r + B_{ins}) \quad (5)$$

Where, B_{ins} is the thickness of insulation layer in m (B_{ins} is such that $5 \le B_{ins} \le 6$ mm (Meriga et al., 2018).

3.1.5 Height of Inductor Coil

Meriga et al. (2018) gave the relation for determining the height of inductor coil as Equation (6).

$$H_{in} = (1.2 - 1.5)H_m \quad (6)$$

$$H_{in} = 0.156\text{m}$$

3.1.6 Height of Inductor Holding Poles

The Height of Inductor Holding Poles is determined as 162 mm using Equation (7).

$$H_P = H_{in} + 2T_f \quad (7)$$

Where, T_f is the flange thickness, taken as 3mm.

3.1.7 Heat Energy and Electrical Parameters

The required theoretical heat energy (Gandhewar et al., 2011), consumed during the first period of melt is given by Equation (8).

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} - Q_{ex} \quad (8)$$

Where, Q_m is the amount of heat energy to melt 5kg of charge material in J, Q_{sh} is Amount of heat energy to superheat the melt to temperature of superheat in J, Q_s is the heat required to melt slag forming materials, in J, Q_{en} is the energy required for endothermic process in J and Q_{ex} is the amount of heat energy liberated to the surroundings as a result of exothermic reactions in J. But, theoretically is $Q_{en} = Q_{ex}$ therefore reducing Equation (8).

$$Q_{th} = Q_m + Q_{sh} + Q_s \quad (9)$$

The amount of heat energy required to melt 5kg of charge material is given by Equation (10) as given by Gandhewar et al. (2011).

$$Q_m = MC(\theta_1 + \theta_0) + L_{pt} \quad (10)$$

Where, M is the mass of charge, kg, C is the specific heat capacity of charge material, (for aluminium, C = 1100J/kg K), L_{pt} is the amount of heat to accomplish phase transformation, (for pure aluminium L_{pt} = 0, phase transformation), θ_1 = melting temperature of charge, (for aluminium θ_1 = 660°C) and θ_0= ambient temperature, 25°C.

$Q_m = 5 \times 1100\ (660 - 25)$

Q_m = 3492500J

Amount of heat energy to superheat the melt to temperature of superheat, Q_{sh} is obtained using Equation (11).

$$Q_{sh} = MC_m\theta_{sh} \quad (11)$$

Where, C_m average heat capacity of molten Aluminum, (= 992J/kg K), θ_{sh} is the amount of superheat temperature, taken as 40°C.

$Q_{sh} = 5 \times 992 \times 40$

$Q_{sh} = 198400$J

Heat required to melt slag forming materials, Q_s is obtained using Equation (12) as given by Gandhewar et al. (2011).

$$Q_s = K_s G_s \quad (12)$$

Where, K_s is quantity of slag formed in (kg), taken as 8% of furnace capacity, G_s is the heat energy for slag = 18kJ/kg.

$Q_s = 0.08 \times 18$

$Q_s = 1.44kJ$

Substituting into Equation (8) yields $Q_{th} = 36910.44$ KJ

3.1.8 Discharge rate of water for coil cooling

Discharge rate of water for coil cooling: from heat, heat balance equation is given as Equation (13) as stated by Bala (2005).

$$Q_p = VA_W\,\rho_W\,C_w\,(\theta - \theta_o) \quad (13)$$

Where, V is the velocity of heat carrying fluid, m/sec, A_w is the cross – sectional area of flow, m^2, ρ_W is the density of heat carrying fluid, Kg/m^3 (1000 kg/m^3), C_w is the specific heat capacity of fluid at constant pressure (4.186 kJ/kg), θ is the outlet temperature of fluid and θ_o is the inlet temperature of fluid

3.1.9 Velocity of heat carrying fluid

Velocity of heat carrying fluid was determined using Equation (14) as stated by Bala (2005).

$$V = \frac{Q_p}{A_W\rho_W C_W\ (P\theta - \theta_o)} \quad (3.25)$$

Where, $A_w = \frac{\pi}{4} \times (0.006)^2$

$A_w = 2.83 \times 10^{-5} m^2$

$$V = \frac{3060.32}{2.83 \times 10^{-5} \times 1000 \times 4186(60 - 25)}$$

$V = 0.74 m/sec$

3.1.10 Discharge of water from tube or flow rate (m^3/sec)

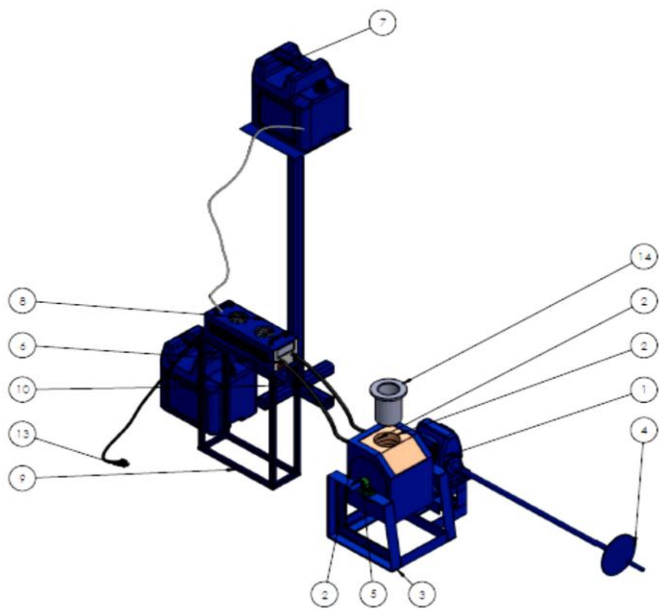
$$Q = VA_w \quad (3.26)$$

$Q = 0.74 \times 2.83 \times 10^{-5}$

$Q = 2.09 \times 10^{-5} m^3/sec$

3.2 Fabrication of Induction Furnace

A mild steel sheet was chosen for the construction of the furnace unit housing and the transformer seat. The thermal conductivity of mild steel is 40.1w/m^{o}/$_{c}$. A 10 litre water container is conjoined to the transformer for easy flow of water into the induction coil and air-cooling using fan for the control board for heat absorption. A high pressure 360 micro pump is used to pump water from the tank into the coil. The pump is selected because of its ability to lift water at a distance of 2.5 meters and transfer of 2 litres/min. The complete set up of the furnace is given in Figure 1. It consists of the transformer, crucible, gear spinner and cooling unit.



ITEM NO.	PART NUMBER	QTY.
1	MANUAL GEAR	1
2	CRUCIBLE HOUSING	1
3	CRUCIBLE HOUSING FRAME	1
4	GEAR SPINNER	1
5	BEARING	1
6	PIPE	2
7	GALLON	2
8	TRANSFORMER	1
9	TRANSFORMER FRAME STAND	1
10	WATER TANK FRAME STAND	1
11	HOSE	1
12	HOSE 2	1
13	CABLE	1
14	CRUCIBLE	1

Figure 1: Working drawing for Induction furnace

3.5 Components of Induction Furnace

a. The Crucible: The crucible is formed from refractory material, which the furnace coils are lined with. This crucible holds the charge material and subsequently the melt.

b. Inductor Coil: The inductor a tabular copper coil with specific number turns. An alternating current (A.C) pass through it and magnetic flux is generated within the inductor. The magnetic flux generated induces Eddy currents in the metal charge. It is these eddy currents that enables the heating and subsequently the melting process in the crucible

c. Cooling System: As a result of the power supplied to the furnace, its circuit appears resistive, and the real power is not only consumed in the charge material but also in the resistance of the coil. This coil loss, as well as the loss of heat conducted from the charge through the refractory crucible requires the coil to be cooled, with water as the cooling medium - this is to prevent undue temperature rise of the copper coil. To achieve effective cooling, a through-one-way flow system is used. The tubular copper coils are connected to water source through flexible rubber hoses, which are being supplied under particular pressure. The Inlet is at the top, while the outlet is at the lower end. The water flow arrangement in much that after every eight turn the water is discharged and a fresh supply starts immediately.

d. Tilting Mechanism: Tilting of the furnace is to effect pouring of the melt as a last operational activity before casting. Due to the small capacity of this furnace, manually operated tilting mechanism is adopted. The furnace is hinged at the spout edge with a shaft and bearings. And at one side to the bearing is a pinion and gear system to give a gear reduction, so that when the handle is turned clockwise, the furnace is tilted to achieve a maximum angle of 90^{o}C for complete pouring of the molten metal by tilting the furnace upwards.

e. Furnace Transformer: A step-down voltage transformer with various voltage steps tap is required. It has a three-phase primary terminal and single-phase output at the secondary terminal. A voltage supply of 415V, 50Hz frequency is used as the primary power supply. The nominal power output of the transformer ranges from 7KVA to 15KVA. The single-phase secondary terminal of the transformer is connected to the furnace inductor coil by means of a water-cooled Flexible copper coil embedded in a rubber hose.

4. Result and Discussion

4.1 Results

Aluminium scarps were deposited into the crucible and melted, from the first test the maximum temperature attained was 720 ^oC in 10 minutes, while the second test carried out attained a maximum temperature of 830 ^oC under 5 minutes.

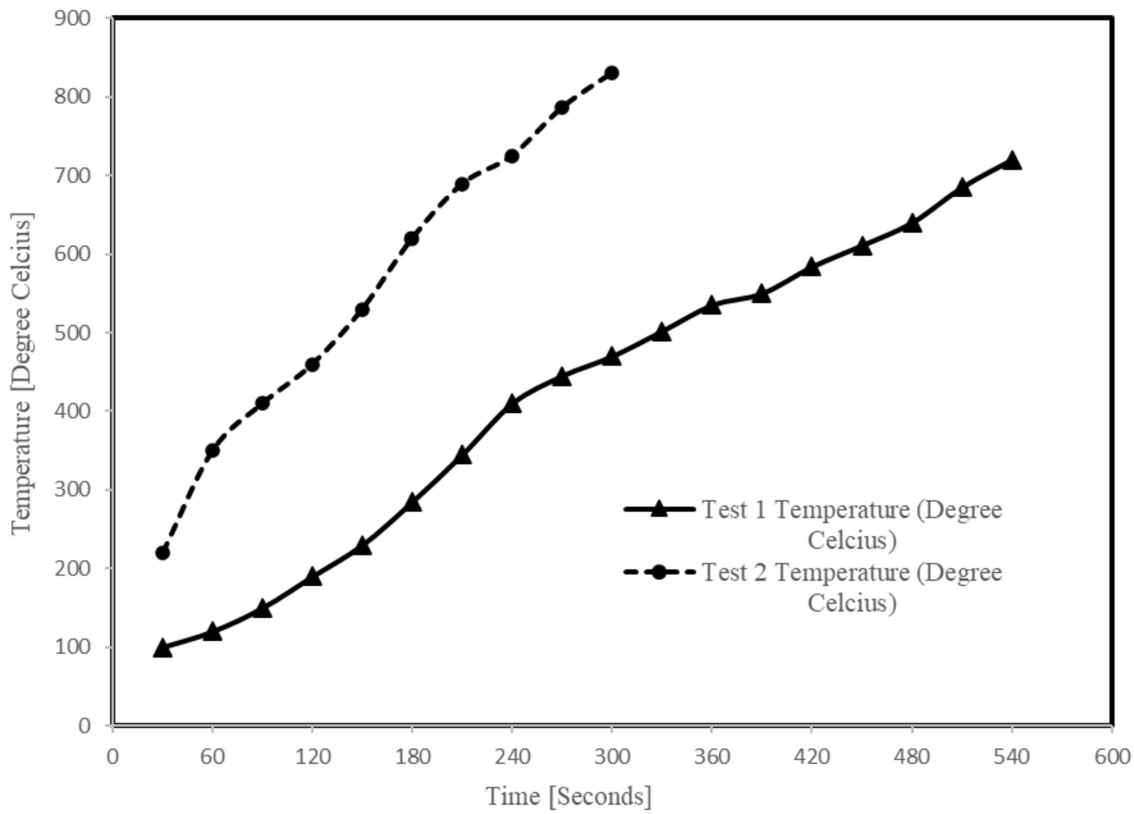


Figure 2: Temperature-Time graph of induction furnace test

4.2 Discussion

For test one carried out the time started up was 30 second and the crucible was heated up to 100 ^oC before the aluminium scrap metal was deposit in the crucible. The maximum temperature of 720 ^oC in 10 minutes, but the second test carried out attained a maximum temperature of 830 ^oC in 5minutes which makes the melting rate higher and faster than test one because the coil was already heated up, so the higher the temperature the faster the metal melts. The fast temperature rise of the second test is due to the preheated condition the furnace was already at when the test was commenced. The furnace was able to achieve an average value of 775 ^oC from the mean of the two tests, which is a satisfactory value considering it is higher than the melting temperature of aluminium.

5. Conclusion

The development of a 5Kg induction furnace for melting aluminium scraps was successfully fabricated and tested. A total heat of 36910.44 KJ was determined analytically for the machine and it reached a temperature of 775 ^{o}C in just 7.5 minutes. The temperature achieved is able to heat and melt the metal (aluminium scrap), in other to achieve the required objective.

The development of this machine helped to reduce aluminium scrap in the environment by increase the awareness of waste management and the recycling of the metal. Air pollution was reduced to the minimal when in operation of the machine and the cost of maintenance and labour was low. The metal (aluminium scrap) was melted in a shortest possible period of time with great reduction in energy consumption.

Therefore, this fabricated induction furnace can be encouraged to be used in our local foundries, companies and institutions in Nigeria and overseas as a medium for learning, faster production and to encourage local production.

References

Adeodu, A., Daniyan, I., Babalola, S., Okojie, F. & Aderoba, A. (2017). Development of a 30Kg aluminium oil-fired crucible furnace using locally sourced materials. *American Journal of Mechanics and Applications* , 5(3), 15-21.

Anaidhuno, U. P. & Mgbenuna C. O. . (2015). Development of an Electric induction furnace for heat treatment of ferrous and non - ferrous alloys. *American Journal of Engineering Research (AJER)*, 4(5), 29-35.

Bala, K. C. (2005). Design Analysis of an Electric Induction Furnace for Melting Aluminum Scrap . *AU Journal of Technology*, 83-88.

Bhamare, R., Wagh, S., More, P., Zole, A. & Sonaye, S. Y. (2017). Design and manufacturing of portable metal melting furnace. *International Conference on Ideas, Impact and Innovation in Mechanical Engineering (ICIIIME 2017)*, 5(6), 748-752.

Bhandari, S. S., Badadal, S. B., Kinagi, V. G., Tuljpurkiar, H. S. & Bansode, S. H. (2018). Design and Fabrication of Crucible Furnaces by using Black Smithy Setup. *International Journal of Engineering and Management Research*, 8(4), 131-134.

Ekpe, E. E., Yahaya, B. S. Achema, F. & Fabiyi, M. O. (2016). Design and fabrication of aluminium melting furnace using locally available materials. *American Journal of Engineering and Technology Research*, 16(1), 12-21.

Gandhewar,V. R., Bansod, S. V. & Borade, A. B. (2011). Induction Furnace - A Review. *International Journal of Engineering and Technology* , 3(4), 277-280.

Meriga, V. S. B., Boyina, A. D. & Vadana, C. (2018). Design and fabrication of low-cost electrical resistance based metal melting furnace for casting applications. *Leonardo Electronic Journal of Practices and Technologies*, 32, 41-54.