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Design Analysis of an Electric Induction Furnace for Melting Aluminum Scrap

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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. The cleanliness and availability of electrical energy sources in Nigeria is of paramount importance to its use in foundries, hence the need for this design. This paper deals principally with the mechanical and electrical requirements for induction furnace production. The mechanical aspect gives consideration to the geometrical components, cooling system, and the tilting mechanism. The electrical aspect deals with the furnace power requirement to make it functional. The design was achieved through consideration of relevant theories and their practical application.

Keywords: *Electrical, Mechanical, Induction, Furnace, Aluminum, Heat energy, Charge, Melting*

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 application 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. Here in Nigeria, Ajaokuta Steel Company and Delta Steel Company are examples of steel making companies 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 (Abubakre 2001), 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.

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, by burning of fossil or organic fuels. These have the disadvantage of producing low quality products as a result of the impurities present in the fuel.

In recognition of these facts, and considering the availability of electricity - a cleaner source of power in Nigeria, the design of an Electric Induction Furnace for Aluminum scrap melting and indeed any metal is in the right direction worth undertaking (Mastrukov 1986).

A furnace is an apparatus in which heat is liberated and transferred directly to solid or fluid charge mass, for the purpose of effecting a physical or chemical change, through cycle involving temperature in excess of 400°C. There exist various classifications of furnaces based on the purpose and energy source.

In the early nineteenth century, the phenomenon of induction heating was applied to the experimental melting of metals. The early furnace consisted of circular hearth or trough, which contained the molten metal of an annular ring. This formed a short circuited single turn secondary winding of a transformer which was energized by a supply of alternating current at normal line frequency. This design has inherent defects, such as mechanical force set up by the current flowing in the molten metal which tended to cause contraction and could result in the interruption of the current, thereby posing operational difficulties. This effect was called ‘pinch effect’ (Shrets *et al.* 1987), and a lot of attempts to solve it were not successful until in the early 1900’s, when Ajax Wyatt removed the difficulty by placing the secondary channel in the vertical plane. The weight of the metal in the bath was then sufficient to overcome the forces, which caused the pinch effect.

It was later that a new approach was made by Dr. E. F. Northrup, who substituted a crucible containing the metal charge in place of the channel (Hammond 1978) surrounded with a multi-turn coil through which current was passed at high frequency. The development of these types of furnaces, the core-type and the core-less type, the former for brass and the latter for steel were extremely rapid, and many hundreds of thousands of kilowatts of capacity are installed throughout the world today.

The poor development of foundries in Nigeria today reported in (Bala 1998) extends to the fact that science and engineering infrastructure was not provided at the beginning of its national independence. However, today there is a good thrust to foundry technology and the trend of induction furnace application is just in its prime age. Its application is mostly in smaller foundries for iron melting.

Basic Components

The induction furnace consists basically of a crucible, inductor coil, and shell, cooling system and tilting mechanism.

The crucible is formed from refractory material, which the furnace coils is lined with. This crucible holds the charge material 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, zirconium oxide (ZrO_2) is implored. The durability of the crucible depends on the grain size, ramming technique, charge analysis and rate of heating and cooling the furnace.

The inductor coil is a tubular copper coil with specific number of turns. An alternating current (A.C) passes through it and magnetic flux is generated within the conductor. The magnetic flux generated induces eddy currents that enable the heating and subsequently the melting process in the crucible. In order to eliminate electrical breakdown the turns are insulated by wrapping with mica tape, this serve as a good insulator.

The shell is the outer part of the furnace. This houses the crucible and the inductor coils, and has higher thermal capacity. It is made of rectangular parallelepiped with low carbon steel plate and joined at the corners by edge carriers from angular pieces and strips of non-magnetic metal.

The cooling system is a through-one-way- flow system with the tubular copper coils connected to water source through flexible rubber hoses. The inlet is from the top while the outlet is at the bottom. The cooling process is important because the circuit of the furnace appears resistive, and the real power is not only consumed in the charged 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 to prevent undue temperature rise of the copper coils.

Tilting of the furnace is to effect pouring of the melt as a last operational activity before casting. Since this furnace is of small capacity, a manually operated tilting mechanism is adopted. The furnace is hinged on at the spout edge with a shaft and bearings. At one side to the bearing is 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 degrees for complete pouring of the molten metal.

Design Analysis

Geometrical parameters

The analysis is based on a 10kg capacity. The shape of the crucible is cylindrical. The internal diameter of the crucible and the height of melt is determined by the furnace capacity (melt volume), with considerations that the ratio:

$$\frac{H_m}{D_c} = (1.6 - 2.0) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 1$$

where H_m = height of molten metal, m;
D_c = diameter of crucible, m;

Volume of metal charge is given by:

$$V_m = \frac{\pi d_m^2 H_m}{4} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 2$$

where d_m = diameter of molten metal = D_c.

The thickness of the refractory lining (Voskoboinikov, *et al.* 1985), of the crucible in the middle of the crucible can determine from the relation

$$B_r = 0.084\sqrt{T} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

where T = furnace capacity in tonnes.

The internal diameter of the inductor can be calculated from the equation:

$$D_{in} = D_c + 2(B_r + B_{ins}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4$$

where B_r = thickness of refractory lining, m;
B_{ins} = thickness of insulation layer.
(B_{ins} is such that $5 \le B_{ins} \le 6$ [mm]).

Height of inductor coil is given by:

$$H_{in} = (1.1 - 1.2)H_m \ldots\ldots\ldots\ldots\ldots\ldots\ldots 5$$

The height of furnace from bottom of the bath to the pouring spout is:

$$H_f = H_m + h_s + b_t \ldots\ldots\ldots\ldots\ldots\ldots\ldots 6$$

where, h_s = height of slag formed, m;
b_t = thickness of bottom refractory lining, (b_t = 25.5mm for 10kg capacity).

The slag height is calculated thus:

$$h_s = \frac{4V_s}{\pi d_m^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots 7$$

where, V_s = volume of slag in one heat, taken as 8% of total charge, m^3.

Height of inductor holding poles:

$$H_p = H_{in} + 2T_f \ldots\ldots\ldots\ldots\ldots\ldots\ldots 8$$

where, T_f = flange thickness, taken as 3mm.

Heat Energy and Electrical Parameters

The required theoretical heat energy (Ilori 1991), consumed during the first period of melt is given by:

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} - Q_{ex} \ldots\ldots\ldots\ldots 9$$

where, Q_m = amount of heat energy to melt 10kg of charge material, J;
Q_{sh} = amount of heat energy to superheat the melt to temperature of superheat, J;
Q_s = heat required to melt slag forming materials, J;
Q_{en} = energy required for endothermic process, J;
Q_{ex} = amount of heat energy liberated to the surroundings as a result of exothermic reactions, J.

Theoretically $Q_{en} = Q_{ex}$.

Where

$$Q_{th} = Q_m + Q_{sh} + Q_s \ldots\ldots\ldots\ldots\ldots\ldots\ldots 10$$

and,

$$Q_m = MC(\theta_1 - \theta_0) + L_{pt} \ldots\ldots\ldots\ldots\ldots\ldots 11$$

where, M = mass of charge, kg;
C = specific heat capacity of charge material, (for aluminum, C = 1100J/kg K);
L_{pt} = amount of heat to accomplish phase transformation, (for pure aluminum L_{pt} = 0, no phase transformation);
θ_1 = melting temperature of charge, (for aluminum θ_1 = 660°C);
θ_0 = ambient temperature, 25°C;

Similarly,

$$Q_{sh} = MC_m\theta_{sh} \quad \ldots\ldots\ldots\ldots\ldots\ldots 12$$

where, C_m = average heat capacity of molten Aluminum, (= 992J/kg K);

θ_{sh} = amount of superheat temperature, taken as 40°C.

and,

$$Q_s = K_s G_s \quad \ldots\ldots\ldots\ldots\ldots\ldots 13$$

where, K_s = quantity of slag formed in (kg), taken as 8% of furnace capacity;

G_s = heat energy for slag = 18kJ/kg.

Total heat energy induced (Hammond, 1978), in charge due to eddy current is given by:

$$Q_{ec} = \frac{\pi^3 f^2 H_m B_{\max}^2 d_m^4}{8\rho} \quad \ldots\ldots\ldots\ldots\ldots\ldots 14$$

where, f = frequency of power supply, 50Hz;

$B_{\max}$ = maximum flux density, H;

ρ = resistivity of charge metal, (for aluminum, $\rho = 2.83 \times 10^{-8}\Omega$m).

Therefore,

$$B_{\max} = \sqrt{\frac{8\rho Q_{ec}}{\pi^3 f^2 d_m^4 H_m}} \quad \ldots\ldots\ldots\ldots\ldots\ldots 15$$

Also

$$Q_{ec} = \frac{Q_{th}}{t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 16$$

where, t = time in seconds to attain maximum flux.

The allowable current density in the inductor is given by:

$$J = \frac{I}{A_t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 17$$

(J ranges from 20 to 40A/mm^2).

where, I = current in inductor in amperes, A;

A_t = cross sectional area of conducting tube (mm^2), take external diameter of inductor coil, d_{t2} = 8mm and internal diameter of inductor coil, d_{t1} = 6mm.

The number of turns of the inductor can be determined from:

$$B_{\max} = \frac{\mu_r \mu_o N I}{L} \quad \ldots\ldots\ldots\ldots\ldots\ldots 18$$

where,N = number of turns of inductor coil;

I = current in coil in amperes, A;

L = H_{in}= length of coil in metres, m;

μ_o = permeability of free space = 4 π x 10^{-7} Hm^{-1};

μ_r = relative permeability of charge material, (for non-magnetic material μ_r = 1).

Therefore,

$$N = \frac{B_{\max} L}{\mu_o I} \quad \ldots\ldots\ldots\ldots\ldots\ldots 19$$

The resistance of the copper coil inductor at ambient temperature is given by:

$$R_{\theta_o} = \frac{\rho_c l}{A_t} \quad \ldots\ldots\ldots\ldots\ldots\ldots 20$$

where, ρ_c = resistivity of copper

=1.72 x $10^{-8}\Omega$m at 25°C;

l = total length of copper tube, m;

= $\pi D_{in} N$

Resistance at any temperature θ is given as:

$$R_\theta = R_{\theta_o}[1 + \alpha\theta_o(\theta - \theta_o)] \quad \ldots\ldots\ldots\ldots\ldots\ldots 21$$

where, $\alpha\theta_o$ = temperature coefficient of copper at 25°C;

= 3.9 x 10^{-3} K^{-1}.

Coil loss due to resistance is:

$$P_c = I^2 R_\theta \quad \ldots\ldots\ldots\ldots\ldots\ldots 22$$

Heat loss through conduction (Shrets *et al.* 1987), from furnace walls to copper coil:

$$Q_L = \frac{\pi H_m(\theta_2 - \theta)}{\frac{1}{2}[\frac{1}{\lambda_{zi}}\ln\frac{d_2}{D_c} + \frac{1}{\lambda_{as}}\ln\frac{D_{in}}{d_2} + \frac{1}{\lambda_{cu}}\ln\frac{d_3}{D_{in}}]} \quad \ldots\ldots\ldots\ldots\ldots\ldots 23$$

where, λ = thermal conductivity, with subscripts for zircon, asbestos, and copper respectively;

λ_{zi} = 2.093w/m K; λ_{as} = 0.117w/ m K; and λ_{cu} = 380w/m K;

d_2 = outer diameter of crucible = D_c + $2B_r$, m;

d_3 = inductor diameter surrounding crucible + 2 thickness of coil, m;

$\theta_2 = \theta_1 + 40°C$ – superheat temperature, °C;

Discharge rate of water for coil cooling is obtained from heat exchange and heat balance relation:

$$Q_p = VA_w \rho_w C_w (\theta - \theta_o) \quad \text{......................} \; 24$$

where, V = velocity of heat carrying fluid, m/sec;

A_w = cross sectional area of flow, m^2

ρ_w = density of heat carrying fluid, kg/m^3;

C_w = specific heat capacity of fluid at constant pressure;

θ = outlet temperature of fluid; °C;

θ_o = inlet temperature of fluid; °C.

Total heat loss per second:

$$Q_p = Q_L + P_c \quad \text{....................................} \; 25$$

Discharge rate in m^3/sec is obtained from the relation:

$$\dot{Q} = VA_w \quad \text{..} \; 26$$

Tilting Mechanism

To be able to pour molten metal easily a tilting mechanism is incorporated to the design.

If F_w = weight of furnace material including charge;

R_w = unrecognized weights = $0.5F_w$;

Total weight of furnace,

$$W_t = F_w + R_w = 1.5F_w \quad \text{..........................} 27$$

The supporting shaft is subjected to both bending and torsional moments. Shaft diameter, d, is given (Hall, et al 1980), by:

$$d^3 = \frac{16}{\pi S_s} \sqrt{(K_b M_b)^2 + (K_t M_t)^2} \quad \text{.............} \; 28$$

where, M_t = torsional moment, Nm;

M_b = bending moment, Nm;

K_t = combined shock and fatigue factor applied to torsional moment;

= 1.0 for load applied gradually to rotating shafts;

K_b = combined shock and fatigue factor applied to bending moment;

= 1.5 for load applied gradually to rotating shafts;

S_s = allowable shear stress;

= 55MN/m^2 for shaft without key way;

= 40MN/m^2 for shaft with key way;

The tilting is effected by the use of mating gears in which the induced bending stress of gear tooth must be less than the allowable stress of gear material, given by the Lewis equation (Hall *et al* 1988) as:

$$S = \frac{2M_t}{m^3 K \pi^2 YN} \quad \text{..................................} \; 29$$

where, M_t = torque on pinion, N.m;

K = constant (K < 4);

N = minimum number of teeth on pinion (N=16);

m = module;

Y = form factor which depends on tooth system and N, (for pressure angle ϕ =20°, N = 16, Y = 0.094).

For approximate value of m in equation (28), S is taken as one third of ultimate tensile stress of material i.e. for carbon steel of 0.5% carbon, UTS = 620MN/m^2.

Velocity Ratio

$$V.R. = \frac{D_g}{D_p} = \frac{N_g}{N_p} \quad \text{...............................} 30$$

where, D_g = diameter of gear. M;

D_p = diameter of pinion, m;

N_g = number of teeth of gear;

N_p = number of teeth of pinion.

Length of tilting handle,

$$L_t = \frac{M_t}{F_a} \quad \text{..} 31$$

where, F_a = average force to be applied for tilting, 550N.

Conclusion

The development of this project from the theoretical aspects to its practical application is of immense contribution to the development of Nigerian foundry technology and to enhance availability of spare parts. The Induction furnace design and subsequently its fabrication should be promoted considering the abundant power sources, less maintenance cost and labor requirements.

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