Design of a Coreless Induction Furnace for Melting Iron

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***Abstract*— This paper deals principally with the design of coreless induction furnaces for melting iron. Both mechanical and electrical requirements for induction furnace have been presented. To verify the design results, a comparison between the design results and those of an actual induction furnace has been carried out.**

***Index Terms*— Induction heating, Coreless induction furnace, Induction Melting.**

I. INTRODUCTION

Induction heating is widely used in metal industry because of its good heating efficiency, high production rate, and clean working environments. The development of high-frequency power supplies provided means of using induction furnaces for melting metals in continuous casting plants [1-4].

Rather than just a furnace, a coreless induction furnace is actually an energy transfer device where energy is transferred directly from an induction coil into the material to be melted through the electromagnetic field produced by the induction coil.

A typical parallel resonant inverter circuit for induction furnace is shown in Fig. 1. The phase controlled rectifier provides a constant DC current source. The H-bridge inverter consists of four thyristors and a parallel resonant circuit comprised capacitor bank and heating coil. Thyristors are naturally commutated by the ac current flowing through the resonant circuit [5].

It is important to select the proper power rating for the system. There are many factors that influence the selection of furnace power. The first is the capacity to be melted, the type of the material to be melted (Iron, Aluminum, Tin ...) and the desired melt cycle time. To raise the temperature of a solid material to the pouring temperature, energy must be put into it based upon the characteristics of its solid specific heat, latent heat of fusion, and liquid specific heat. An improperly designed system that has an undersized power supply will reduce the efficiency of the overall system and reduce the weight of metal that can be melted per kWh applied. This could result in the inability for the system to reach the required pour temperature [2].

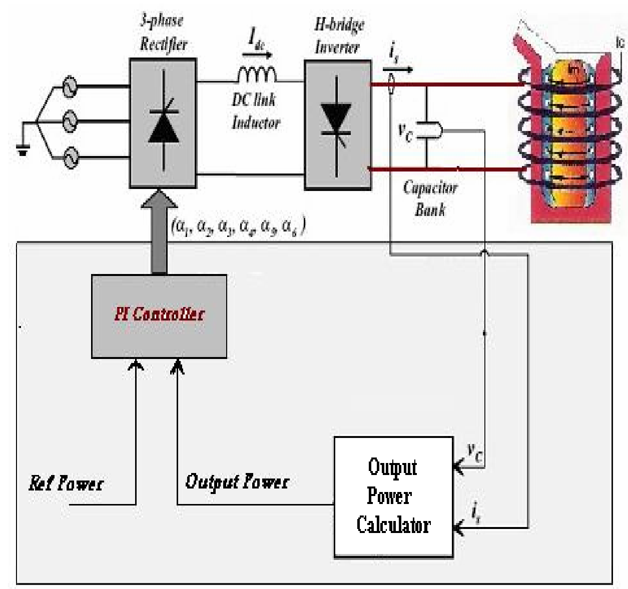

Fig. 1. Block diagram of induction furnace system

In this paper a design of coreless induction furnace for melting iron has been introduced. The design includes both mechanical and electrical requirements. The mechanical aspect gives consideration to the geometrical parameters while the electrical aspect deals with the coil design, the optimum induction frequency and the electric power required by the furnace.

II. Design Analysis

The analysis is based on 4 tons capacity of molten iron.

A. Geometrical Parameters

The coreless induction furnace consists basically of a crucible, inductor coil, shell, cooling system and tilting mechanism. The crucible is formed from refractory material, which the furnace coil 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. The durability of the crucible depends on the grain size, ramming technique, charge analysis and rate of heating and cooling the furnace [3]. Figure 2 shows typical components of a coreless induction furnace [2].

The geometric shape of the furnace is shown in fig.3.

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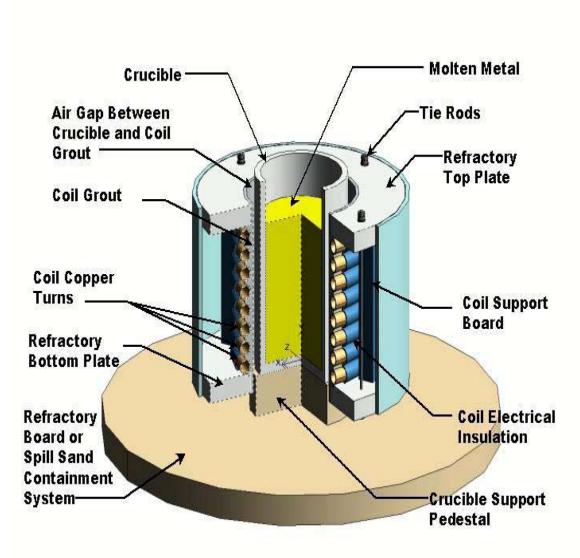

Fig. 2 Typical Components of a coreless Induction Furnace

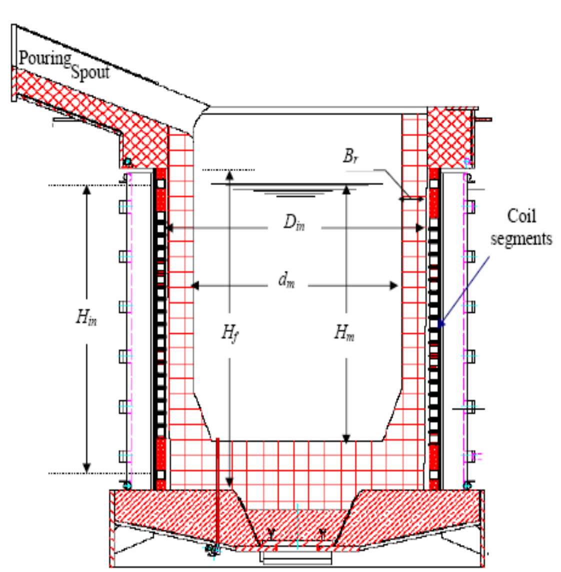

Fig. 3 The geometric shape of the furnace

The shape of the crucible is cylindrical. The internal diameter of the crucible (the diameter of melt) and the height of melt are determined by the furnace capacity with considerations that the ratio [3]

$$\frac{H_m}{D_c} = 1.6 \rightarrow 2\,; \tag{1}$$

Where H_m = height of molten metal (m)

D_c = diameter of crucible (m) .

The volume of metal charge is given by:

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

Where d_m = diameter of molten metal (m) = D_c

Also, $$V_m = \frac{M}{\rho_V} \tag{3}$$

Where M = the mass of charge in kg

ρ_V = the density of charge material in kg/m^3

The thickness of the refractory lining of the crucible can be determined from the relation:

$$B_r = 0.084\sqrt{T} \tag{4}$$

Where T = furnace capacity in tones

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

$$D_{in} = D_c + 2(B_r + B_{ins}) \tag{5}$$

Where B_{ins} = thickness of insulation layer

($5.5 \le B_{ins} \le 6$ mm)

Height of inductor coil is given by:

$$H_{in} = (1.1 \rightarrow 1.2) H_m \tag{6}$$

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

$$H_f = H_m + h_s + b_t \tag{7}$$

Where h_s = height of slag formed = 4% of H_m

b_t = thickness of bottom refractory lining

= 20 cm for 4 ton capacity.

B. Heat Energy Parameters

The required theoretical heat energy, Q_{th}, consumed during the first period of melt is given by:

$$Q_{th} = Q_m + Q_{sh} + Q_s + Q_{en} - Q_{ex} \tag{8}$$

Where,

Q_m = amount of heat energy to melt 4 tons of charge material, Joule.

Q_{sh} = amount of heat energy to superheat the melt to temperature of superheat, Joule.

Q_s = heat required to melt slag forming materials, Joule.

Q_{en} = energy required for endothermic process, Joule.

Q_{ex} = amount of heat energy liberated to the surroundings as a result of exothermic reactions, Joule.

Theoretically $Q_{en} \cong Q_{ex}$.

Therefore,

$$Q_{th} = Q_m + Q_{sh} + Q_s \tag{9}$$

$$Q_m = MC(\theta_1 - \theta_0) + ML_{pt} \tag{10}$$

Where, C = specific heat capacity of the charge material, J/kg.k°

L_{pt} = latent heat of fusion, J/kg

θ_1 = melting temperature of charge, k°

θ_0 = ambient temperature, 25°C (298 k°)

Similarly,

$$Q_{sh} = MC_m\theta_{sh} \tag{11}$$

Where, C_m = average heat capacity of molten metal, J/kg.k°

θ_{sh} = amount of superheat temperature, taken as 330 and,

$$Q_s = K_s G_s \tag{12}$$

Where, K_s = quantity of slag formed in (kg), taken as 4% of furnace capacity;

G_s = heat energy for slag = 300 kJ/kg.

C. Electrical Parameters

Figure 4 shows a melted cylindrical load put inside the furnace, the total heat energy induced in it, can be calculated as follows [6]:

Assume an element path of thickness (*dx*) with radius (*x*) from the vertical axis, and a sinusoidal flux $\varphi = \varphi_m \sin \omega t$, where

$$\varphi_m = B_m \cdot A \quad \text{Wb} \qquad (13)$$

Then

$$\varphi = \pi x^2 B_m \sin \omega t \qquad (14)$$

The induced e.m.f (*e*) is given by:

$$e = \frac{d\varphi}{dt} = \pi \omega x^2 B_m \cos \omega t \qquad (15)$$

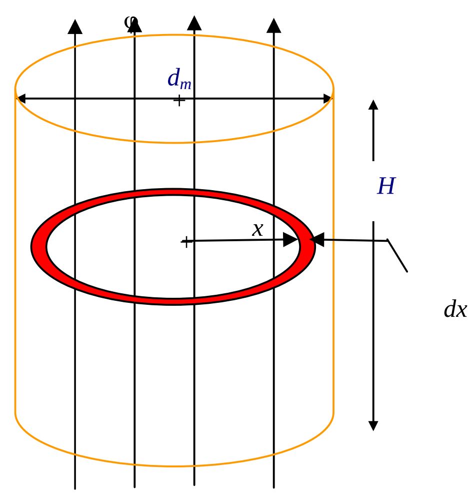

Fig. 4 A melted cylindrical load

The effective value of this e.m.f (*E*) in the element path is:

$$E = \frac{2\pi^2 f x^2 B_m}{\sqrt{2}} \qquad (16)$$

If ρ is the resistivity of the material, the resistance of each elemental path is,

$$R = \frac{\rho l}{A} = \frac{\rho 2 \pi x}{H_m dx} \qquad (17)$$

The eddy current flows in the metal can be calculated from the equation:

$$I_m = \frac{\pi x f H_m B_m}{\sqrt{2} \rho} dx \qquad (18)$$

Since the current flows on the outer layer of the metal , equations (17) and (18) can be rewritten as:

$$R = \frac{\rho \pi d_m}{H_m d_o}, \text{ and } I_m = \frac{\pi d_m f H_m B_m}{\sqrt{8} \rho} d_o$$

Where d_o is the skin depth and is given by [2]:

$$d_o = \sqrt{\frac{\rho}{\pi \mu f}}$$

The total eddy current dissipated in the charge is

$$P = I_m^2 R \quad \text{W} \qquad (19)$$

$$P = \frac{\pi^3 f^2 H_m d_m^3 B_m^2}{8 \rho} \sqrt{\frac{\rho}{\pi \mu f}} \quad \text{W} \qquad (20)$$

Where, μ is the permeability of charge material which is equal to $\mu_o \mu_r$, where μ_o is the permeability of free space and μ_r is the relative permeability. Since at about 1100 °C temperature, the permeability of the iron is equal to that of air [4], i.e., $\mu = 4\pi \times 10^{-7}$ Wb/A.m,
so in equation (20), $\mu = \mu_o$.
B_m = maximum flux density (Tesla)
R = Resistance of charge material = R_L (Ω)
I_m = current flowing in metal *(A)*

From equation (20)

$$B_m = \sqrt{\frac{8 \rho P}{\pi^3 f^2 H_m d_m^3 d_o}} \qquad (21)$$

The power (*P*) can be calculated from the theoretical heat energy Q_{th} calculated from equation (9) as:

$$P = \frac{Q_{th}}{t} \quad \text{W} \qquad (22)$$

Where *t* = the total time of melting in seconds

The induction furnace can be considered as a transformer with single turn short circuited secondary. Figure 5 shows the equivalent circuit of the furnace coil with load based on the transformer concept [7], from which

$$I_{coil} = \sqrt{\left[\frac{I_m}{N}\right]^2 + (I_o)^2} \quad \text{A} \qquad (23)$$

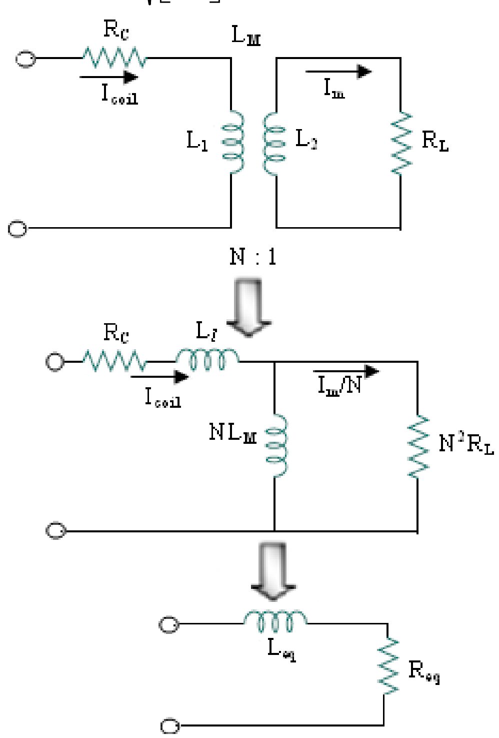

Fig. 5 the equivalent circuit of induction furnace based on transformer concept

Multiplying both sides by N, equation (23) can be written as:

$$NI_{coil} = \sqrt{(I_m)^2 + (NI_o)^2} \quad \text{A.T} \qquad (24)$$

Since $NI_o = Hl$, then $N = \frac{1}{I_{coil}} \sqrt{(I_m)^2 + (Hl)^2}$,

and $H = \frac{B}{\mu}$ A.T/m

$$N = \frac{1}{I_{coil}} \sqrt{(I_m)^2 + \left(\frac{B_m l}{\sqrt{2}\,\mu} \right)^2} \tag{25}$$

Since, the self inductance of the coil L_1 is given by:

$$L_1 = L_l + NL_M \quad \text{H}$$

Therefore,

$$L_l = L_1 - NL_M \quad \text{H} \tag{26}$$

Where $L_1 = \frac{\mu_o \mu_r N^2 A}{l}$,

$A = \frac{\pi D_{in}^2}{4}$ and $l = H_{in}$

The voltage across the load is equal to

$$\frac{I_m}{N} N^2 R_L = I_o NL_M \omega \quad \text{V}$$

The referred load resistance $R_{ch} = N^2 R_L$, therefore,

$$NL_M = \frac{\sqrt{2}\, I_m R_{ch} \mu_o \mu_r}{B_m\, l\, \omega} \tag{27}$$

Substituting from (27) in equation (26)

$$L_l = \frac{\mu_o \mu_r N^2 A}{l} - \frac{\sqrt{2}\, I_m R_{ch} \mu_o \mu_r}{B_m\, l\, \omega} \tag{28}$$

Since all magnetic energy is stored in air gaps, insulation between conductors, and within the conductor where μ_r is essentially 1.0 and constant, therefore $\mu = \mu_o$ [7]. So,

$$L_l = \frac{\mu_o N^2 \pi D_{in}^2}{4 H_{in}} - \frac{\sqrt{2}\, I_m R_{ch} \mu_o}{B_m\, H_{in}\, 2\pi\, f} \tag{29}$$

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

$$R_c = \frac{\rho_c\, l_c}{A_t} \quad \Omega \tag{30}$$

Where ρ_c = resistivity of copper
= $1.72 \times 10^{-7}\ \Omega\, m$ at 25 °C

l_c = total length of copper tube = $\pi D_{in} N$ m

A_t = cross sectional area of conducting tube m^2

$$A_t = \frac{I_{coil}}{J} \quad \text{m}^2 \tag{31}$$

Where J = current density (ranges from 20 to 40A/mm^2 for water cooled tubing conductor)

Since I_o is very small compared with I_m/N, NL_M can be neglected with respect to R_{ch}. Therefore, the equivalent resistance $R_{eq} = R_c + R_{ch}$ and the equivalent inductance $L_{eq} = L_l$

D. Selection of Induction Frequency

The frequency affects both the coupling efficiency of the electromagnetic field to the charge and the stirring characteristics of the molten metal in the furnace [2]. For optimal furnace performance, the selection of the system operating induction frequency is very important. The chart in Fig. 6 describes the relation between the induction frequency and the furnace size for different melting conditions [8]. An ideal melting can be determined when the frequency and the furnace size is interacted on the center line in the middle zone.

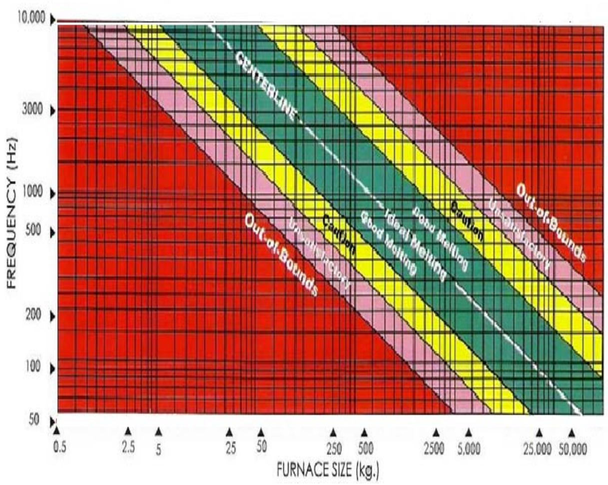

Fig. 6 Relation between the induction frequency and furnace size

III. Furnace Design

The thermal parameters of iron, which is considered as a charge material is shown in Table 1 [9-11].

Table 1 Thermal parameters of iron

	Parameter	Value	unit
1	Specific Heat Capacity	460	*kJ/kg.k°*
2	Melting Temperature	1573	*k°*
3	Latent Heat	267	*kJ/kg*
4	Electrical resistivity	0.1	*μΩ-m*
5	Temperature coefficient	56e-3	--
6	Density	7000	*kg/m³*

The geometrical and the electrical design parameters were determined by applying equations (1) through (31). The results are tabled in Tables 2 and 3.

IV. Comparison between Actual and Calculated Parameters

To verify the design results, a comparison between some of these results and the corresponding ones of an actual induction furnace were carried out. The actual furnace is manufactured by ABB Company in Germany. It is 4 ton capacity working at resonance frequency of 250 Hz, with 3 MW maximum power, 3000 V maximum voltage and 1500 A maximum current. A comparison between some electrical and geometrical parameters of the designed furnace and the actual one is shown in Table 4. From this table, it can be seen that the design parameters are close to the actual ones.

Table 2 Geometrical parameters of the furnace

	Parameter	**Value**	**unit**
1	Volume of the charge (*Vm*)	0.5714	m^3
2	Diameter of melt *(dm)*	76.90	*cm*
3	Height of melt (*H*m)	123	*cm*
4	Thickness of the refractory lining *(Br)*	16.8	*cm*
5	Internal diameter of the inductor *(Din)*	111.5	*cm*
6	Height of inductor coil (*Hin*)	135.3	*cm*
7	Height of furnace from bottom of the bath to the pouring spout *(Hf)*	147.96	*cm*

Table 3 Electrical parameters of the furnace

	Parameter	Value	unit
1	Optimum Operating frequency *(f)*	250	*Hz*
2	Resistance of charge material (*RL*)	0.0512	*m*Ω
3	Current in the metal (*Im*)	232.57	*kA*
4	Power required to melt the charge in 20 minutes (*P*)	2.766	*MW*
5	Coil tube cross sectional area (A_t)	814	mm^2
6	Coil current (*Icoil*)	11.803	*kA*
7	Number of coil turns (N)	20	*turns*
8	Coil resistance (*RC*)	1.5	*m*Ω
9	Equivalent resistance (*Req*)	21.90	*m*Ω
10	Equivalent inductance (*Leq*)	0.19014	*mH*

Table 4 Comparison between actual and calculated parameters

	Parameter	Calculated value	Actual value
1	Number of turns of the coil (*N*)	20 turns	20 turns
2	Equivalent inductance (L_{eq})	0.19 *mH*	0.192 *mH*
3	The volume of the charge (V_m)	0.5714 m^3	0.5714 m^3
4	The diameter of melt (d_m)	76.90 *cm*	85 *cm*
5	The height of melt (H_m)	123 *cm*	107 *cm*
6	The thickness of the refractory lining (B_r)	16.8 *cm*	10.5 *cm*
7	The internal diameter of the inductor (D_{in})	111.5 *cm*	107 *cm*
8	The height of the inductor coil (H_{in})	135.3 *cm*	131.5*cm*

V. Conclusion

This paper presented a design of coreless induction furnace for melting iron. Both mechanical and electrical requirements for induction furnace were considered. The geometrical parameters of the furnace such as diameter of melt, the height of melt, and diameter of coil were determined directly by the furnace capacity. The heat energy required to melt the charge material depends on the solid specific heat, latent heat of fusion, and liquid specific heat of the charge material. From which, the power required to melt the material was determined. The electrical parameters of the furnace such as number of turns of coil, inductance of the coil, resistance of the coil and the maximum flux density were determined based on transformer concept, where the furnace is represented by a transformer with N primary turns and one secondary tune that is short circuited. The design results were verified by comparing the design results with the corresponding ones of an actual induction furnace. The comparison shows good agreement between both results.

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