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Analysis of the Efficiency of Induction Melting of Oxides in cold Crucible Based on Mathematical Modelling

Buganji Dele Masobeji[1]; Baseer Ahmed[2];
Barakur Calvin Azo[3]; I.V. Pozynyak[4] (Professor)

[1;2;3;4]Department of Electrotechnology and Converter Engineering,
St. Petersburg Electrotechnical University "LETI" St. Petersburg, Russia

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Abstract: This paper is intended to address the study and analysis of the efficiency of the process induction melting of metal oxides in cold crucible based in mathematical models. Experimental set up and computer software tools such as ANSYS and Microsoft excel computational tools were used for obtaining data and the analysis. Some reviews were studied to obtain references and more details for the analysis.

Keywords: *Cold Crucible, Induction Melting, Oxides, Analysis, Efficiency, Mathematical Modelling.*

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I. INTRODUCTION

For many years induction heating and melting has been in operation in metallurgical and in the manufacturing industries. In order to obtain a melt of the of oxides, nowadays crucibles are fundamentally needed for which the melting point of the melt will be higher than melt temperature.

Induction melting in a cold crucible is a technology used for melting oxides and other materials with high melting points. The cold crucible technique involves using an induction heating system to generate eddy currents in a conductive crucible, which causes the material inside to melt.

The complexity of the induction melting system with cold crucible is on the influence of the cold crucible in the efficiency of the system.

One of the advantages of using a cold crucible for induction melting is its high efficiency, as the heat is generated directly in the material without any contact with a hot crucible. The purity of the product is another advantage of the induction melting technology which differentiate from the ordinary technologies[1].

This results in minimal heat loss and energy consumption during the melting process.

Mathematical modelling is used to optimize the induction melting process in a cold crucible, taking into account factors such as material properties, crucible design, and power input. By simulating the heating and melting process using mathematical models in ANSYS computational tool, we can improve the efficiency and effectiveness of the cold crucible melting technique.

In general, induction melting in a cold crucible is a credible technology for melting oxides and other high-melting-point materials with the potential for increased efficiency and control through mathematical modelling and optimization.

II. SYSTEM SETUP

The entire induction system comprises a power section containing facilities and a data collection system. The objective of the melting process is to transform a sample of pure metal oxide, specifically in the melt, without any additional impurities.

The figure 1 below shows the induction system with cold crucible.

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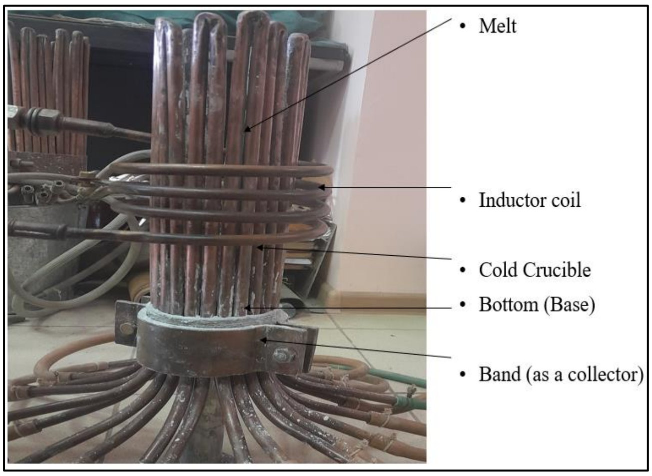

Fig 1 Inductive Cold Crucible System.
(Photo from LETI Department).

The cold crucible (CC) is used as a melting dish to hold the metal oxides under study. The inductor coil for inductively heating the oxides inside the crucible. The bottom(base) is the end potion of the crucible where the metal oxides are placed or positioned. The Band (collector) is used to hold tightly the crucible segments. The melt is the intended product during the process.

The experiment was carried out in many steps. Firstly, the cold crucible was prepared for melting. Then, the load consisting of pure metal oxide in powder form, was inserted into the cold crucible. Finally, the beginning material, pure metal material, was inserted into the load.

The melting process involves several steps. First, the starting material is heated to its melting point. Then, the load is gradually added to a cold crucible while the melting is taking place. The cold crucible is shifted vertically against the inductor during this process.

The output power is carefully controlled. The entire load is melted and maintained at a steady temperature of 2500°C and above depending on the metal material for a specific duration. After that, the induction heating is stopped, and the load is cooled down in a controlled manner to obtain the ingot of the melt[2].

The generator generates the power supply (AC) voltage to the inductor coil which then generates alternating magnetic field that circulates in the load via CC. The load is heated by the physical phenomena of eddy current and hysteresis. In operation, eddy currents (I_e) go against the magnetic field applied to the load and produce the heating effect by joule effect. The magnetic hysteresis generates additional heating in ferromagnetic materials[3].

➢ *Stages of Melting Process in Cold Crucible*

This process of melting considers the energy utilization concept. The cold crucible induction systems consider the variation of energy consumption with different crucible parts[4].

The figure12 below describes the stages of induction melting in cold crucible and the energy consumption.

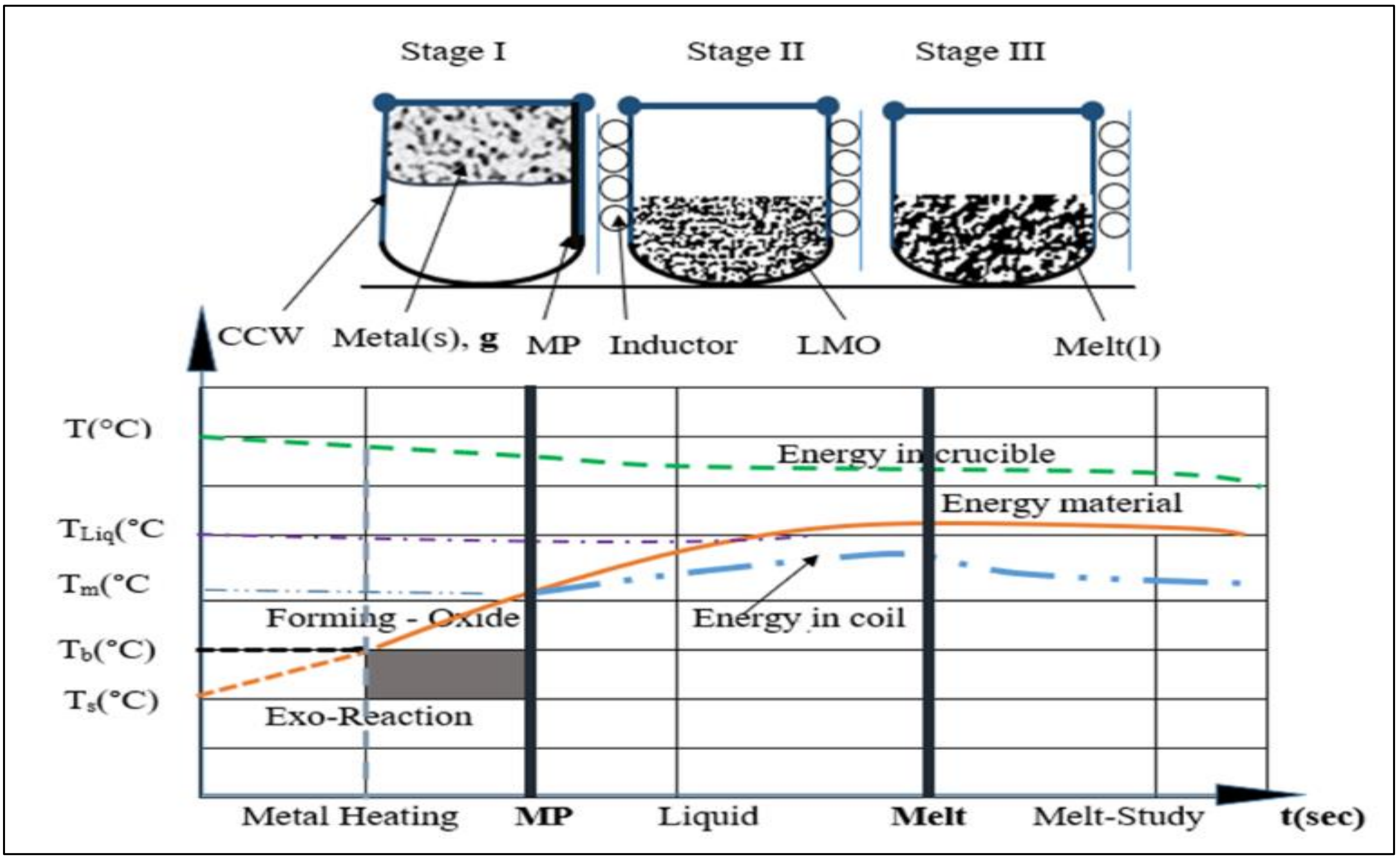

Fig 2 Stages of Melting Processes in CC.

III. MATHEMATICAL MODELLING

The mathematical modelling of the process is the approach for analysing the electromagnetic and thermal effects in the metal oxides during heating and melting processes.

Mathematical model used in this study is the Finite Element Method FEM.

The induction system is divided to areas, where electromagnetic phenomena are describing by integral (interior problem) or differential (exterior problem) equations. Electromagnetic field in the melt is defined by means of finite element method (FEM)[5]. Influence of sources (current in the inductor and crucible parts) is taking into account by means of magneto-coupled circuits.

3D electromagnetic equations are changing to 2D by means of accounting only φ (radial coordinates system) component of current vector in the crucible. It allows consider the slitted crucible as pairs of one-loop solenoids with antiphase currents in the model. IEM allows easy to account it by introducing of additional conditions in global coefficients matrix. Radial components of current vector in the neighboring crucible parts create electromagnetic flux with different direction and superposition of the flux is about zero. Results of physical and numerical experiments are shown that accepted assumption in suggested mathematical model is correct

According to the secondary sources method electromagnetic field in conductive region is calculated using conduction currents. Fredholm's equation second kind describes a distribution of current density J in conducting non-magnetic region.

$$r_k = \frac{P_k}{\Delta S_2 \cdot \sigma_k} N$$

Were P_k - segment perimeter (length of current way in segment), N – number of segments of the crucible.

Internal problem is described by 2D differential equation relative vector magnetic potential:

$$\frac{1}{\mu_0}\left(\frac{\partial^2 \dot{A}}{\partial R^2} + \frac{1}{R}\frac{\partial \dot{A}}{\partial R} + \frac{\partial^2 \dot{A}}{\partial z^2} - \frac{\dot{A}}{R^2}\right) = j\omega\sigma\dot{A}$$

Equation is solved by FEM were functional is written as [7]

$$F = 2\pi\int_s \frac{1}{2\mu_o}\left[r\left(\frac{\partial \dot{A}}{\partial z}\right)^2 + \frac{\dot{A}^2}{r} + 2\dot{A}\frac{\partial \dot{A}}{\partial r} + r\left(\frac{\partial \dot{A}}{\partial r}\right)^2\right]dS + j\omega\sigma\pi\int_s r\dot{A}^2 dS$$

Using FEM for solution interior problem is defined by complicated shape of pool melt. Boundary conditions for internal problem is defined along to perimeter of area S_2 as[6]

$$\dot{\vec{A}}_i = \frac{1}{4\pi}\int_S \frac{(\dot{\vec{J}}_j, \vec{r})}{r^2} dS$$

For investigation of magnetic field in any space point is used Biot-Savart law.

$$\dot{\vec{H}}_i = \frac{1}{4\pi}\int_S \frac{[\dot{\vec{J}}_j, \vec{r}]}{r^3} dS$$

Solution of the equation system (66 - 68) is realized by block-iteration method[7] and its coupling is shown at figure 14.

IV. RESEARCH RESULTS

➢ *Experiment Method*

The experimental results are are discussed base on the observations.

Fig. 2. Diameter of the particles of the starting material (Al)

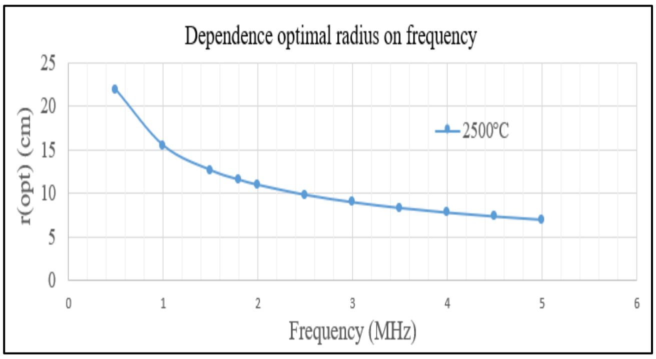

Fig 3 Dependence radius on working frequency.

If we want to know radius of melted aluminium oxide, we need to know density of aluminium and ratio between r_4 and a_4:

(Density) $\rho_{Al2O3(2500°C)} = 3950\ \left({}^{kg}/_{m^3}\right) = 3{,}95\left({}^{g}/_{cm^3}\right)$

We expect ratio between r_4 and a_4:

$$a_4/r_4 = 0{,}5 \rightarrow a_4 = 0{,}5 \cdot r_4$$

We know:

$$\rho_{Al(2500°C)} = \frac{m_4}{V_4} \rightarrow V_4 = \frac{m_4}{\rho_{Al(2500°C)}} = \frac{7{,}98}{3{,}9} = 2{,}021(cm^3)$$

Where, m_4 is weight of liquid aluminium oxide (1.6) created from 1g of aluminium and V_4 is volume of expected cylinder. Radius of cylinder is then:

$$V_4 = \pi \cdot r_4^2 \cdot 0{,}5 \cdot r_4 \ \rightarrow r_4 = \sqrt[3]{\frac{V}{\pi \cdot 0{,}5}} = \sqrt[3]{\frac{2{,}021}{\pi \cdot 0{,}5}} = 1{,}088\ (cm)$$

Table 1 Experiment Method

Weight of starting material Al (g)	Liquid Al2O3 - 2500°C (g)	V (cm^3)	r_4 (cm)
1	7,98	2,02	1,09
5	39,92	10,11	1,86
7	55,89	14,15	2,08
10	79,84	20,21	2,32
12	95,81	24,26	2,49
15	119,76	30,32	2,68
20	159,69	40,43	2,95

➢ *Results Analysis and Evaluation*

Testing of mathematical model was based on comparison of results of physical and numerical experiments. It was examined two systems, one of them included inductor and crucible and the other – inductor and melt without crucible, see table 6.

After testing of mathematical model, influence of melt parameters to energetic characteristics was investigated. Sketch and basic dimensions of investigated induction system with slitted crucible is shown at figure 17. Resistivity and depth of melt pool was variable parameters. Numerical experiments have been done for power source frequency 90 kHz. Results of the numerical experiments are presented at Fig. 3-6, which demonstrate the quantitative and qualitative changing of power losses in the crucible and melt, and electrical efficiency of induction system and magnetic field distribution. Dependence of power losses in the crucible via melt parameters is more interesting and important results from our point of view. Power losses is increasing if the melt pool depth is increasing and/or its resistivity is decreasing.

This phenomenon has to be taken in to account in technological processes where melt pool depth is changed and heat sources must be stabilized. The heat sources can be determined from numerical calculation only. One more area of using of suggested model is solving of inverse problems to investigate the melt properties.

Table 2 Experimental and Calculations Data

Basic dimensions	**$D_{cr.\ ext}$=7.3 cm $D_{cr.\ int}$=5.3 cm h_{ind}=6.5 cm D_{ind}=9.4 cm W_{ind}=5**		**h_{melt}=90.0 cm D_{melt}=103.6 cm h_{ind}=100.0 cm D_{ind}=133.6 cm W_{ind}=31**	
	Experimental data	Calculation	Experimental data	Calculation
T_{me}, °C	-	-	800.0	
f, Hz	$1.82 \cdot 10^6$		50.0	
U_{ind}, V	1720.0		283.4	
I_{ind}, A	-	-	1382.0	1404.9
P_{melt}, kW	-	-	-	35.6
$P_{crucible}$, kW	0.73	0.70	-	-
$P_{ind.losses}$, kW	0.80	0.67	-	17.91
$P_{ind.act}$, kW	-	-	51.77	53.30
$P_{ind.re}$, kVA	-	-	388.20	394.58
cosφ	-	-	0.132	0.134
σ_{me}, $(\Omega cm)^{-1}$	-	-	$0.42 \cdot 10^5$	

* Table 2 - The ratios of the Power in the crucible and Melt

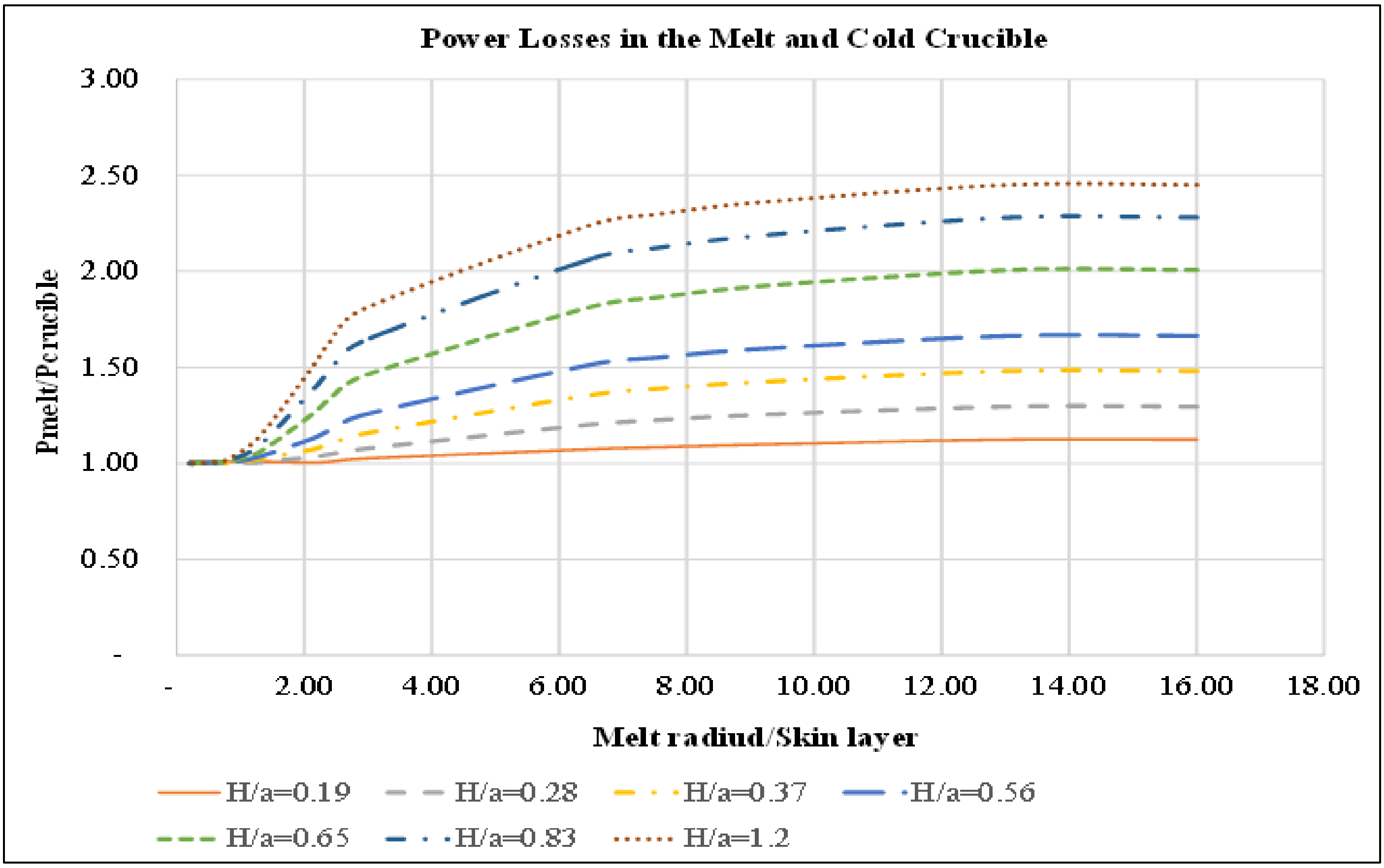

Fig 4 Power Ratios in the Melt and Crucible

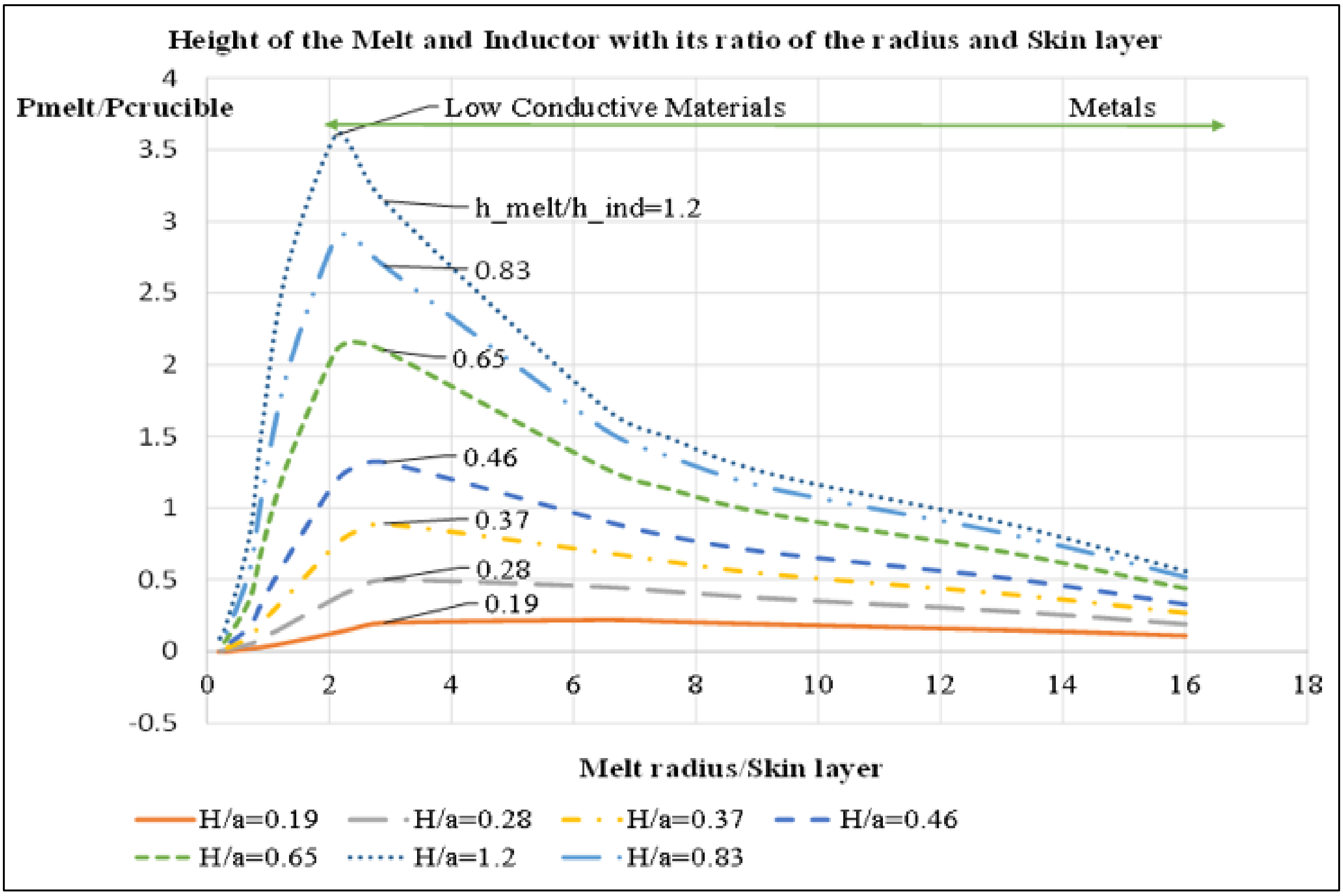

Fig 5 Power loses with the melt radius and skin layer

- Figure 5 - Relation between power losses in the melt and crucible

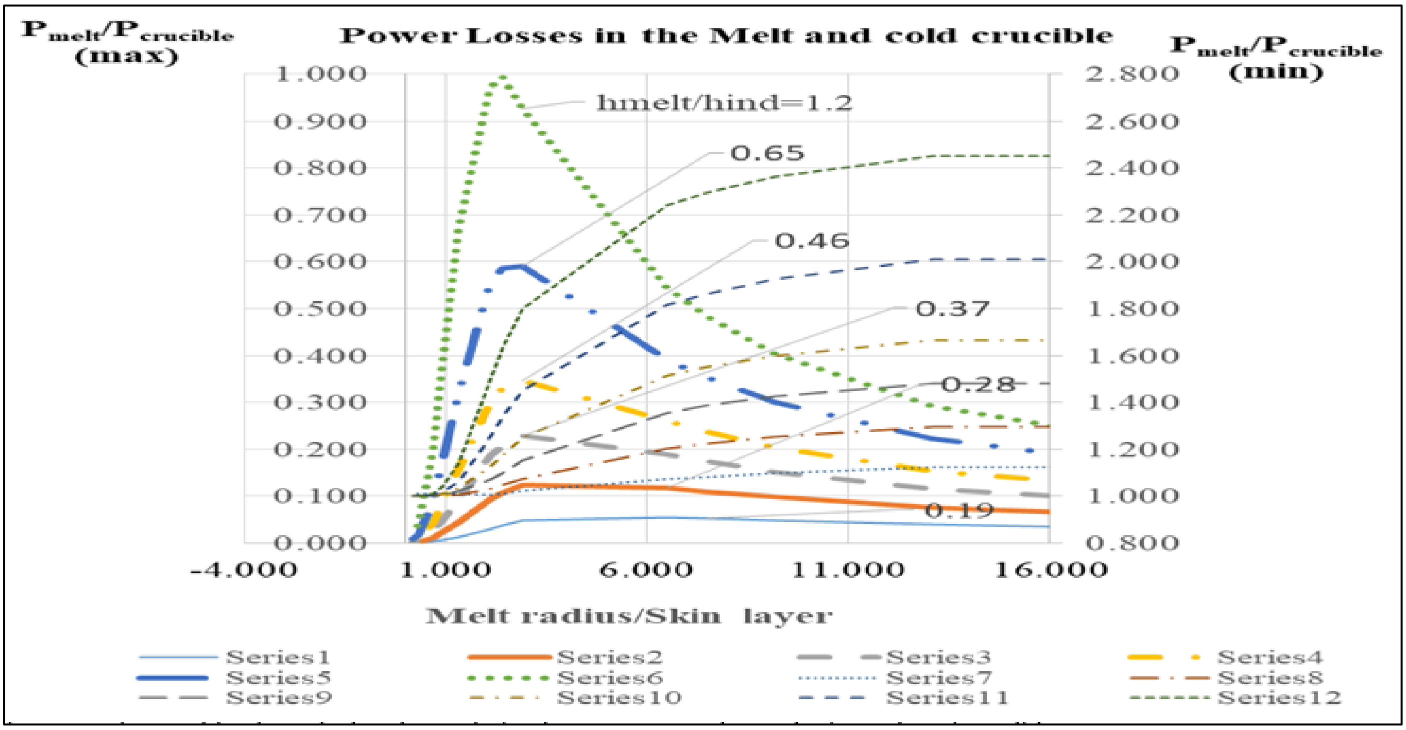

Fig 6 The Combined Graph showing Relation between Power Losses in the Melt and Crucible

➢ *The Heating Efficiency of the Crucible*

The efficiency of the inductor and the crucible is calculated

We know that, the depth of penetration

$$M_2 = \frac{\sqrt{2} \cdot R}{k_1\sqrt{f}} = \frac{R_2}{\Delta}$$

Where M_2 is the ratio between the Melt height and Inductor height; R_2 is the resistance of melt; k_1 is the coefficient.

$$k_1 = \frac{530}{\sqrt{f}}$$

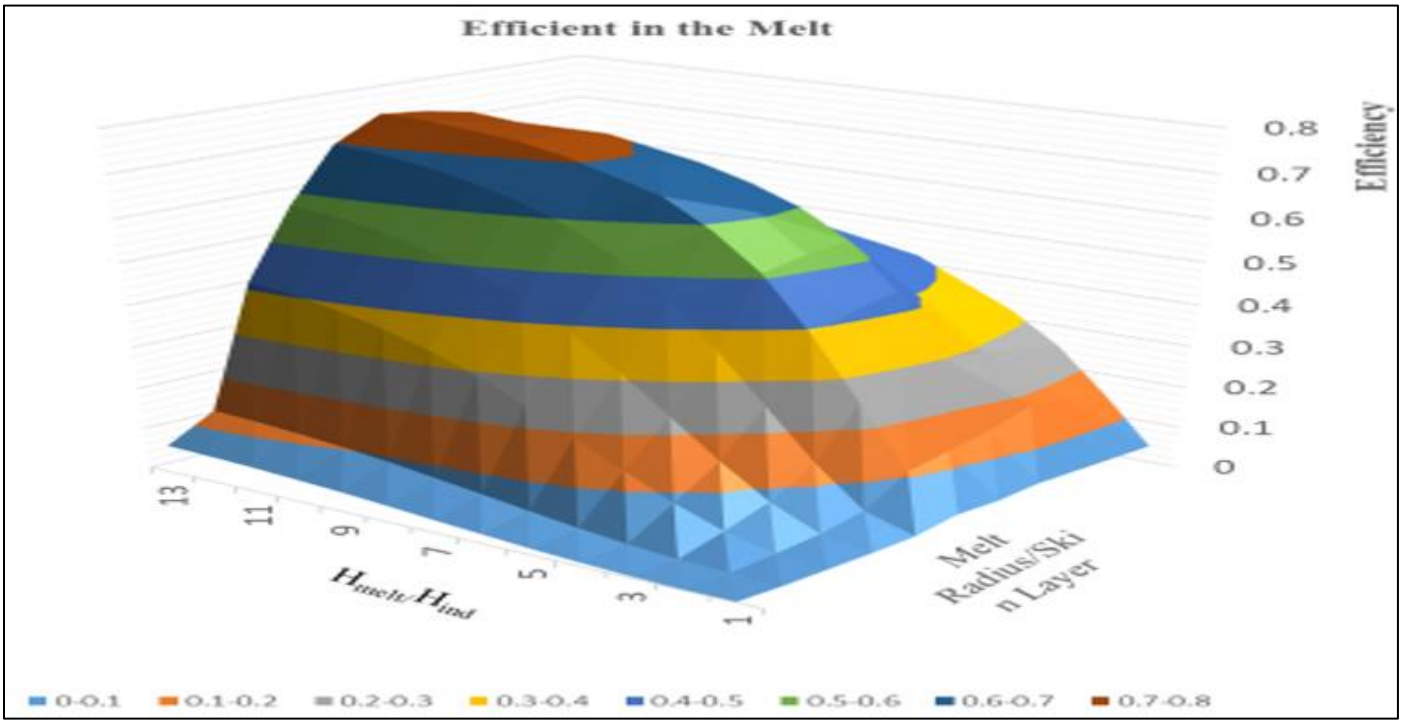

Fig 7 Electrical Efficiency in the Melt in cold Crucible Induction System.

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$$k_1 = \frac{530}{\sqrt{f}}$$

$$\Delta_2 = 503\sqrt{\frac{\rho_2}{\mu f}}$$

$$\eta_e = \frac{P_u}{(P_{cond} + P_{conv} + P_{rad})} \cdot 100\%$$

From table 6 above the power in input (Pu) is calculated as the product of the Voltage and current in the inductor in the especially the less or nonconductive metal oxides.

Where η_e is the electrical efficiency; $P_u = V \cdot I$ is the useful power equals the input power ; $(P_{cond}, P_{conv}, P_{rad}$ are the power losses in due to conduction, convection and radiation respectively.

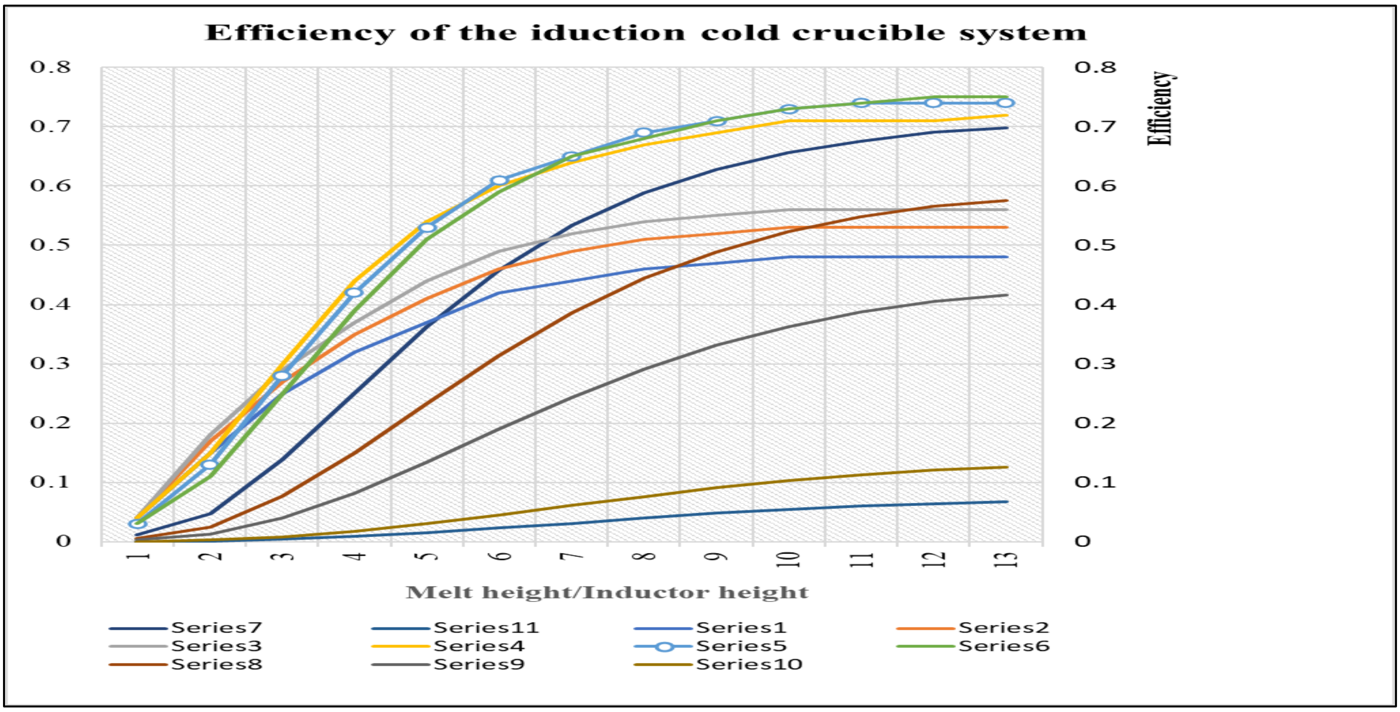

Fig 8 Electrical Efficiency Distribution in the Melt in cold Crucible Induction System.

With the cold crucibles the cooling process is maintained thus minimizing the heating and power losses in the system.

As the case involved in high temperatures safety issues were also given comments so that all working individuals must watch for lifeguarding. Figure 8 – Showing the linear efficiency variation in the induction crucible system

V. CONCLUSION

Cold crucible induction melting technology is currently employed in metallurgical process and manufacturing industries. Because of the need of higher temperature and efficiency for such scientific spheres, the study and the analysis of the parameters and efficient becomes a crucial aspect.

This study has described the analysis of the heating and melting efficiency of the process of induction with cold crucible based on mathematical models in which the supply of electrical power to the system is taken into account as well the losses involved in the system.

The method is incredibly cool process of induction melting. The efficiency is shown higher.

➢ *Abbreviation and Definitions*

- ANSYS-Analysis System
- CC- Cold Crucible
- IMCC-Induction Melting in Cold Crucible
- ISMT-Induction Skull Melting Technology
- IFCC- Induction Furnace Cold Crucible
- MHD – Magnetohydrodynamic
- LMO-Liquid meatal oxide

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