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ANALYTICAL AND EXPERIMENTAL METHOD ON OVERALL HEAT TRANSFER COEFFICIENT OF THE INDUCTION FURNACE I.7506

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Abstract

In an induction furnace, the electrical energy transforms into heat by kanthal wire magnetic field in refractory jacket. The construction of smelting furnace I.7506 consists of ladle in the refractory jacket's interior and the exterior is isolated with refractory brick and glass wool and strengthened with steel plate. Two primary requirements of a melting furnace are the ladle temperature $50\text{-}100^{\circ}\mathrm{C}$ above the melting point of the metal and low heat loss. The radiation heat transfer as effective heat and conduction heat transfer as lost heat are demonstrated by the ladle temperature and steel plate. The purpose of this research is to refine smelting operation and reduce energy consumption and heating loss.

In this experiment, the heat effective and heat loss were observed by measuring the electrical current and voltage of the kanthal wire. Every 15 minutes, the observation data of electric energy consumption and the temperature of ladle, refractory jacket, and steel plate were

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retrieved. This research utilized several tools such as induction electric furnace I.7506, Ampere-Volt clamp meter, infrared thermometer gun, and stopwatch.

The heat transfer inside the furnace plays a significant role in determining thermal efficiency. The longer the furnace operates, the more energy consumption and heating loss it takes. However, in the eighth 15 minutes, the energy consumption tended to decrease and the heating loss kept increasing. The profile of theoretical and experimental temperature demonstrated similar tendency, yet the experimental value was less than the theoretical value.

1. Background

The estimation of heat energy necessity in smelting process needs to be accurate and precise. The heat estimation data can influence casting quality and efficiency. The efficiency of aluminum and its alloy smelting in the induction furnace (59.76%) is higher than gas fueled furnace (reverberatory 30-45%). The smelting method does not only affect energy consumption and cost of casting, but can also be used to control the quality, composition, and physical and chemical characteristics of casting products (Ambade et al. [1]). According to Gandhewar et al. [2], induction furnace provides quick smelting cycle of 30-35 minutes with automatic stirring effect and high smelting power of 0.7-1.0kWh/kg Al. Estimating heat energy accurately and precisely is a thoughtful measure in aluminum casting industry.

Metal casting prioritizes *quantity* over *quality*, especially in small industry of die casting such as aluminum and its alloy. However, the crisis of energy and raw material that hits the manufacturing industry drives the industrialists to be selective and efficient in utilizing resources. Today, such a consideration is renounced. Quality is now above quantity in casting products. According to Kvande and Drabløs [3], estimating the energy consumption of smelting is significant for the casting manufacturers to cut production cost by improving the smelting process such as replacing coal fuel with electric energy for generating heat energy.

Generally, smelting furnace has relatively low smelting efficiency because of a considerable amount of heat loss from raw material holes and liquid metal. Naranjo et al. [4] stated that the disadvantages of smelting furnace depend on the furnace design, energy used, and heat application to the metal (object). Induction furnace (IF) I.7506 is a modified smelting furnace with mechanic opening hole. IF I.7506 is designed for low frequency with smelting temperature of $750^{\circ}C$ and smelting capacity of 6kg aluminum for each filling. Several advantages of IF I.7506 are clean smelting result, easy temperature adjustment, homogeneous liquid composition, high efficiency of heat energy, possible smelting for several non-ferrous materials, and low investment.

The comparison of the materials' characteristics and specific gravity influences the characteristics of applicative material such as composite. Today, the components or engineering products (smelting furnace I.7506) use high strength-to-weight ratio materials. Boadu and Lin [5] confirmed that a composite of graphite and copper is more efficient in increasing heat spreading compared to high thermal conductivity of a traditional material with high weight (copper). On the other hand, a composite of ceramic and glass wool has extraordinary ability as an isolator to store heat from conventional material with high specific gravity of ceramic (Sanoj and Kandasubramanian [6]).

2. Methods

Figure 1 shows the induction furnace I.7506 that was analyzed theoretically and experimentally in this research. The basis of theoretical approach was the heat propagation design of smelting furnace that was made of ladle, fireproof stone, heat isolator, and steel plate. The data of theoretical temperature was acquired from the calculation by incorporating the furnace's geometry (shape and dimension). The experimental approach was performed by operating the smelting furnace with electric voltage control of ± 220 Volts and measuring the current. The experimental data is the record of temperature measurement of every 15 minutes in refractory jacket, ladle and steel plate. The theoretical and experimental data were then plotted in a superposition graph and analyzed.

Figure 1. Induction furnace in research: (a) starting operation and (b) state in operation.

2.1. Analytical of steel plate and ladle temperatures

In this study, the heat balance of the heating furnace can be performed based on the data obtained by the field measurement. Since the furnace is operated under the steady state condition, the heat balance is presented in a schema of heat transfer as shown in Figure 2:

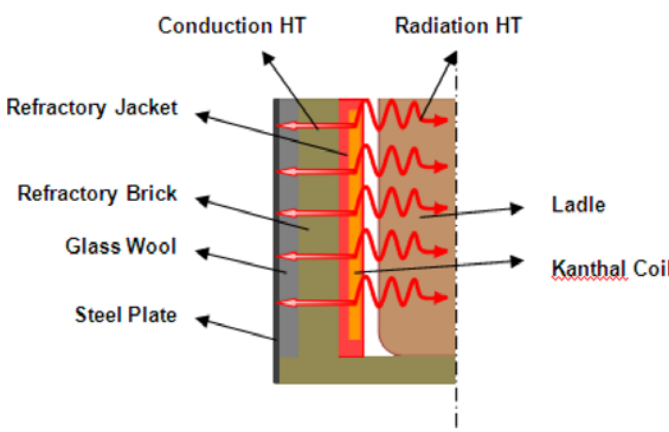

Figure 2. Schema of heat transfer of induction furnace system.

The electric consumption of the induction smelting furnace to generate heat energy (temperature) of refractory jacket follows the equation:

$$q_e = CcIV \cos\varphi \text{ [kcal]}, \tag{1}$$

where C: conversion factor kWH to kcal is 859.85, c: multiplying factor to 15 minutes is 0.25, I: electrical current, V: electrical potential, and cos φ: power factor is 0.85.

Heat energy of an object is commonly transferred by conduction, convection and radiation. In smelting furnace, the heat transfer of solid media conduction (refractory jacket, refractory bricks, glass wool, steel plate) is the development of Fourier law as stated in the equation:

$$q_c = k_c A_m \frac{T_{rj} - T_{sp}}{X_c}, \tag{2}$$

where $q_c, k_c, A_m, T_{rj}, T_{sp}, X_c$ each represents heat energy transferred by conduction (heat loss) [kcal], conductivity coefficient of material mixture $[\text{W/m.K}]$, mean area of heat loss $[\text{m}^2]$, jacket refractory temperature [K], steel plate temperature [K], thickness of induction furnace wall [m], respectively.

The coefficient of refractory jacket, refractory bricks, glass wool, steel mixture such as specific gravity of composite or alloy is determined with the rule of alloy (Suprapto et al. [7]) with the following formulation:

$$k_c = \%t_{rb}k_{rb} + \%t_{gw}k_{gw} + \%t_{sp}k_{sp}, \tag{3}$$

where $\%t$ is the fraction of material thickness [m].

Convection heat transfer in the construction system of induction smelting furnace did not occur, since the airflow or gas flow was very minimum. The internal diameter of heated refractory jacket will radiate the heat to the ladle. The heat radiation inside the induction furnace is formulated as follows:

$$q_r = \varepsilon A_l \sigma (T_{rj}^4 - T_l^4), \tag{4}$$

where ε: emissivity $(0 < \varepsilon < 1)$, A_l: ladle surface area $[\text{m}^2]$, σ: Stefan-

Boltzmann constant $[5.67 \times 10^{-8} \mathrm{W/m^2.K^4}]$, and T_l: ladle temperature [K], respectively.

The energy balance in the induction smelting furnace system is stated into:

$$q_e = q_c + q_r + q_{storage}, \tag{5}$$

where $q_{storage}$ is the storage heat.

Then each energy (q) is stated with the temperature change of the mass body (m) following the equation:

$$E = mCp\Delta t, \tag{6}$$

where the mass *m* of material ladle is 1.00kg, refractory jacket is 9.60kg, refractory brick is 45kg, glass wool is 2.5kg, and steel plate is 16.5kg. Also, *Cp* the specific heat of material to ladle is 0.92kJ/kg.C, refractory is 1.05kJ/kg.C, glass wool is 0.67kJ/kg.C, and steel plate is 0.45kJ/kg.C.

In the induction smelting furnace system I.7506, E_{rj} of some of the heat is stored, radiated onto the ladle, and transferred by conduction through refractory brick, glass wool isolator, and steel plate. The efficiency of smelting energy theoretically can be calculated from the comparison of *the theoretical energy required to smelt the metal added with raising temperature to pouring temperature* divided by the sum of actual consumption of smelting energy, material treatment, holding and moving material. Mathematically, the energy efficiency is stated into:

$$\text{Energy efficiency} = \frac{\text{Theoretical energy required}}{\text{Actual energy used}} \times 100\%. \tag{7}$$

2.2. Experimental of refractory jacket and ladle temperatures

In this study, the mode of heat transfer is not the only means to present heat quantity required to reach high temperature, but the heat efficiency is also important in determining the smelting productivity. Therefore, it requires the analysis on the influence of individual heat transfer mode in smelting furnace. A mathematical expression was developed to analyze the contribution of individual heat transfer mode, which is expected to be beneficial in increasing thermal efficiency. This study also covers the analysis of temperature profile (experimental and theoretical) during the operation of the furnace. The experiment also involved layered insulation materials such as refractory brick, glass wool, and steel plate to recognize the effects on the temperature characteristics of the furnace.

Every 15 minutes, the electric value (current and voltage) was measured with Ampere-Volt meter, and the furnace temperature such as ladle (T_l), refractory jacket (T_{rj}) and steel plate (T_{sp}) were measured using thermocouple. The temperature measurement of ladle and refractory jacket was performed quickly by opening the input/output hole of the induction furnace. After the hole was closed, the measurement of electric value and temperature of steel plate was then performed. The measurement was stopped in the tenth 15 minutes because the temperature of the ladle reached 800°C. Figure 3 displays the measurement of electric power consumption (*I*, *V*) and the points of temperature of the ladle, refractory jacket, and steel plate of the smelting furnace I.7506 during the experiment.

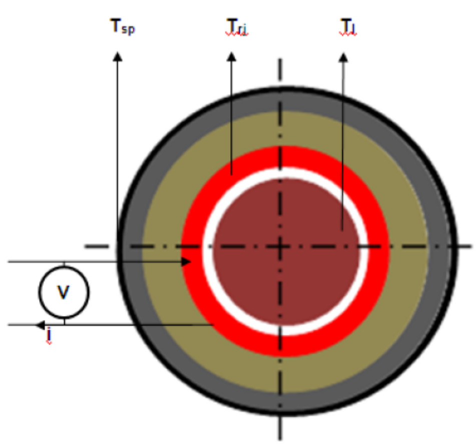

Figure 3. Points of temperature measuring on experiment.

2.3. Instrument of experiment

1. Induction furnace I.7506

Electric power supply: Current $= 11\text{-}13$ Ampere,

Potential $= 200\text{-}220$ Voltage, Frequency $= 50$Hz,

Max. temperature: 1000°C, Max. capacity: 6kg Aluminum,

Weight: 50kg.

2. Infrared thermometer

Model: TM-969, Resolution: $0.1 < 1000^\circ C$ or $1 > 1000^\circ C$,

Measurement range: –60 to 1000°C,

Power supply: DC 1.5V AAA (UM-4) battery × 2 Pcs.,

Weight: 386g.

3. Results and Discussion

This experiment observed the effect of electrical parameters on the conduction and radiation heat transfer of heated refractory jacket as shown in Table 1. The conduction heat transfer with 2 insulation media (refractory brick and glass wool) and 1 conductor medium (steel plate) was performed with one temperature setting. The conductivity thermal was measured with the setting of heat total absorption from the heat input of the heat generation. The radiation expression of the external surface of refractory jacket was determined by the emissivity and geometry factor with valid assumption as in equation (4). Therefore, it is simple to explain that the ladle only received radiation heat emission. The cavity between the refractory jacket and the ladle can be related by the fact that such a ladle was not in direct contact with the heat surface. The result of the analytical test in Table 2 used equation (6). The total of theoretical heat absorbed by the ladle then could be calculated.

Table 1. Thermal energy (q) analytical as a function of operating time of induction furnace

Time [minutes]	Electrical input		Heat generated		Heat [kcal] of		
	Current	Potential			Jacket	Ladle	Steel plate
	[Amp.]	[Volt]	[kWh	(kcal)]			
15	12.08	200.0	0.41	(353.16)	321.42	38.30	5.98
30	12.00	204.0	0.39	(335.47)	314.15	53.48	6.66
45	12.17	207.0	0.38	(331.42)	314.15	78.79	7.35
60	12.18	207.0	0.37	(322.48)	318.28	124.13	8.04
75	12.12	207.0	0.35	(297.97)	321.68	151.87	8.74
90	12.25	211.9	0.33	(284.58)	320.62	166.39	9.44
105	12.30	210.8	0.30	(260.57)	313.89	186.42	10.12
120	12.41	211.0	0.31	(263.15)	306.97	200.07	10.79
135	12.40	213.0	0.31	(265.43)	313.89	207.11	11.47
150	12.18	210.0	0.32	(271.07)	290.05	210.85	12.11

Table 1 shows a complete heat movement model as exposed by equation (5) that is applied to the induction smelting furnace. Figure 4 illustrates the measured temperature graphic lower than the analysis because it was assumed that the latent heat was ignored in the calculation. In fact, the total of heat absorbed during the furnace operation was equivalence with the total of heat to overcome the load of latent heat, such as the water evaporation latent heat in the smelting furnace.

The conduction heat transfer as the influence of the furnace's air temperature is not significant, yet the air relative humidity and the water content of the furnace material otherwise present a significant influence (Xiao et al. [8]).

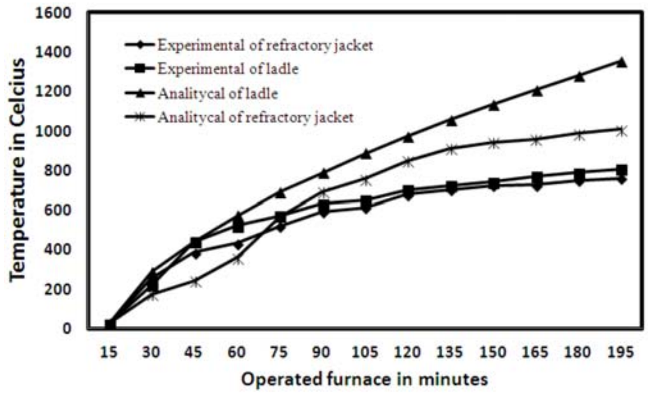

Figure 4. A comparison chart of analytical and experimental temperatures of induction furnace.

According to Gadpayle and Baxi [9], induction furnace basically consists of ladle, coil inductor, steel plate (shell), cooling system, and slug disposal mechanism (tilting) with non-contact heating. In smelting furnace system I.7506, the conduction heat transfer zone 1 passed through 10cm of refractory brick $(k = 0.04\text{W/m.K})$, 2cm of glass wool isolator $(k = 0.34\text{W/m.K})$, and 0.02cm of steel plate $(k = 40\text{W/m.K})$. The heat total of an object can be stated with the heat absorption expressed by the conductivity and radiation of the emission cover and geometric factors (Venkateshmurthy and Raghavarao [10]).

Generally, the calculation data is different from the experimental data because the assumption of heat transfer calculation used single body. In fact, the material consists of soft laminates called *fiber stream*. The research on the induction furnace heat transfer with the basic coefficient calculation of mixed heat transfer can deliver a near-similar calculation and experimental data. Sholapurwalla and Scott [11] expressed that the result of heat transfer is accurate and precise when the calculation is based on layered (composite) or formed material. The heat energy from the refractory jacket is classified into two heat transfer zones as follows: (1) The zone of outer diameter $(\varnothing = 15.5\,\text{cm})$ to the steel plate generated by induction. (2) The zone of outer diameter $(\varnothing = 12\,\text{cm})$ to the ladle generated by radiation.

Table 2 demonstrates that thermal property changes of the material inside the smelting furnace during the operating are determined by the temperature (color). Kodur and Khaliq [12] concluded the thermal properties of a material (concrete) such as specific heat, thermal conductivity, and thermal expansion, as the function of temperature. The primary material of the smelting furnace is the aggregate mixture of mineral materials with ceramic-like characteristics and nature. In high temperature, the conductivity and diffusivity as the thermal properties of the crystalline aggregate material (refractory) decrease, yet the specific heat increases (Naus [13]).

Table 2. Temperature gradient and thermal properties of furnace elements

Time [minutes]	Temperature gradient [°C]						Thermal properties			
	Analytical			Experimental			k_c	ε	Cp	Color
	R. Jacket	Ladle	S. Plate	R. Jacket	Ladle	S. Plate				
15	261	150	3	231	196	1	0.028	0.90	0.04	Brown
30	153	69	3	130	220	5	0.025	0.90	0.04	Brown
45	133	115	3	47	80	0	0.025	0.90	0.06	Brown
60	116	206	3	86	50	1	0.021	0.90	0.06	Brown
75	97	126	3	72	60	3	0.021	0.85	0.08	Red
90	97	66	3	21	20	11	0.021	0.85	0.08	Red
105	87	91	3	66	52	1	0.018	0.85	0.10	Red
120	82	62	3	24	18	1	0.018	0.85	0.10	Red
135	80	32	3	19	20	1	0.018	0.85	0.15	Red
150	71	17	2	5	30	1	0.018	0.75	0.15	Orange

In Figure 5, the result of the experimental method initially demonstrates higher thermal efficiency than analytical method. However, after the furnace had been operating for 1 hour (4×15 minutes), the thermal efficiency of analytical method was higher exceeding the experimental one. This is caused by the fact that the water content inside the furnace is experimentally noticed, yet analytically ignored (zero). The heat absorbed in the evaporation and released by the condensation generated heat on the surface, with a temperature higher than the atmosphere of the furnace. The humid surface influenced the surface temperature and the comparison of sensible heat to latent heat could increase surface temperature rapidly, yet the temperature increase was gradual when dry. Therefore, the water content in the refractory jacket would increase the permeability so that the radiation heat was high, yet it only occurred in the beginning of the operation. On the other hand, after the internal atmosphere of the furnace was dry, the radiation heat permeability decreased so that the experimental efficiency was less than analytical efficiency.

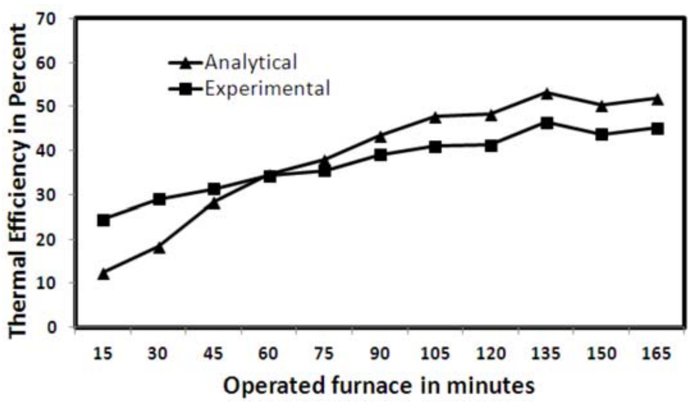

Figure 5. Thermal efficiency of induction furnace I.7506.

4. Conclusion

The heat generation of electric coil (kanthal wire) in the heater jacket was transferred by radiation to the ladle and by conduction to the steel plate. Both the heat transfers held a significant role in determining the heating efficiency (smelting). Therefore, the amount of heat provided by the radiation and conduction heat transfer was regulated by the total of electric energy supplied to the induction smelting furnace in order to achieve the expected heat efficiency. The mathematical expression was significantly applied to calculate the amount of heat and the contribution of each individual heat transfer mode, which is eventually beneficial to modify the design of the induction smelting furnace. The profile of theoretical and experimental temperatures demonstrated similar tendency, yet the experimental value was less than the theoretical value.

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