Temperature Estimation of Liquid Steel in Induction Furnace

Anuwat Pansuwan, Krit Smerpitak and Prapart Ukakimaparn

***Abstract*—This article presents the indirect measures of temperature by measuring the energy put into the furnace, temperature and flow rate of cooling water and temperature at the outer wall lining of the induction furnace in order to estimate the temperature of the liquid steel in the furnace. The technique for estimating the temperature relies on the consideration of the heat balance equation of the furnace and the use of several parameters for the furnace during the processes in order to estimate the losses of heat from the furnace in order to calculate the heat balance equation. From this method, we can estimate the temperature of liquid steel in the induction furnace accurately.**

***Index Terms*—Induction Furnace, Heat Balance, Heat Loss, Latent heat, Heat Model.**

I. Introduction

This research relates to the measure of the liquid steel temperature in the indirect electric induction furnace and the design of heat balance equation with the objective to increase the efficiency for energy saving and quality of liquid steel by consistently controlling the melting process. The important problem of the melting process is that we cannot measure the temperature of the liquid steel temperature continuously since the direct measure of temperature by thermocouple has some restrictions in that the measure of temperature cannot be performed continuously since the liquid steel has high temperature of 1560 degree Celsius and there are some mixed substances in the liquid steel. The life span of the temperature meter is short if putting it in the liquid steel for a long time. The inability to continuously measure the temperature leads to the inefficiency of the control of temperature of liquid steel during the melting process so the energy and the quality of liquid steel are loss.

In order to develop the melting process, it is necessary to realize the temperature of liquid steel and from the restrictions of the direct measure of temperature, we design the methods for measuring the temperature of liquid steel. This methods presented depend on the estimation of the liquid steel temperature from the measure of energy put into the furnace, the temperature, and flow rate of the cooling water system and the temperature at the outer wall lining of the furnace, and we conduct the experiment to estimate the loss heat during processes. Then, such values are used to estimate the temperature of liquid steel by using the heat balance equation.

Manuscript received December 16, 2008
Anuwat Pansuwan is with the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Ladkrabang, Bangkok, 10520 Thailand (e-mail: dome_anuwat@hotmail.com, s8060858@kmitl.ac.th)
Krit Smerpitak is with the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Ladkrabang, Bangkok, 10520 Thailand (e-mail: kskrit@kmitl.ac.th).
Prapart Ukakimaparn is with the Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Ladkrabang, Bangkok, 10520 Thailand (e-mail: kuprapar@kmitl.ac.th)

II. Heat Model

In order to find the heat model of the furnace, we use the heat balance equation of the furnace for consideration. The pattern of heat balance equation is as follows.

$$\text{Heat input} = \text{Heat output} + \text{Heat loss} \quad (1)$$

Energy	Equation
Heat Input	P_{in}
Heat Given to Steel	$Q_S = \frac{m_S \cdot L}{\Delta t} + \frac{m_S \cdot C_{PS} \cdot \Delta T_S}{\Delta t}$ (2)
Heat Loss From Electricity	$Q_T = 4 \cdot I_{INV}^2 \cdot R_{CU}$ (3)
Heat Loss during the Cooling Water Process	$Q_W = M_W \cdot C_{P,W} \cdot \Delta t_W$ (4)
Heat Loss from the Heat Induction of the Furnace Wall	$Q_C = \frac{T_S - T_W}{R} \cdot 10^{-3}$ (5)
Other Heat Losses	Q_{th}

Where

m_S = Mass of Steel (Kg)
L = Latent heat of steel (kJ/kg)
C_{PS} = Volume of the Heat of Steel (kJ/kg °C)
M_W = Flow rate of cooling water (kg/sec)
C_{PW} = Volume of the Heat of water (kJ/kg °C)
T_S = Temperature of liquid steel (K)
T_W = Temperature of cooling water (K)
Δt = Melting time (sec)
R = Heat resistance of the furnace lining (kW/K)

R_{CU} = Resistance of the coli in the converter (Ω)

I_{INV} = Current of Inverter (A)

The heat input is the electricity energy input. The heat output is the heat directly given to the steel consisting of the heat for increasing the temperature of steel and latent heat of the steel. Upon considering the loss heat of the furnace, we have found 2 natures of the heat losses, namely, heat losses (heat) and heat losses (electricity).

Upon considering the heat losses (heat), they consist of the heat losses from transferring the heat from furnace wall to the coil, the heat losses from radiation at the furnace, heat losses from the heat induction of the cooling water system, and other heat losses. The mechanism for the heat losses depends on the temperature and upon considering the heat losses (electricity), they consist of the heat losses in the converter, the heat losses in the inverter, heat losses in coil, and other heat losses. The characteristics of the losses depend on the volume of electricity and resistance.

Several variables related to the equation and that can be measured consist of the electricity power put into the furnace, the temperature of liquid steel in the furnace, the temperature of input and output cooling water, flow rate of cooling water, and mass of steel to find the heat model of the furnace system designed. We attempt to get the variables from the heat incurred in the furnace so we can measure and the estimated temperature is closet to the temperature in the actual furnace as much as possible. We have found that the heat given to the steel in the process of measuring the liquid steel temperature is the processes that the steel in the furnace becomes the liquid so there is no latent heat. We have found only the heat that increases the temperature. Hence, we can cut this part of heat from the study. We have also found that the heat that increases the temperature is the function of the liquid steel temperature in the furnace $f(\Delta T_S)$. Upon considering the heat loss in the converter, we have found that it is the function of the resistance and flow. Both the resistance and flow depend on the electricity power input. Thus, we can summarize that the heat loss in the converter is the function of electricity power input $f(P_{in})$ regarding the heat loss in the cooling system. This part of heat is the heat used for transferring the heat to the coil system of the furnace, which is the function of the flow rate of the heat induction, namely, the heat from liquid steel in the furnace that passing out of the furnace wall, which is the function of the liquid steel temperature in the furnace $f(\Delta T_S)$ and other heat losses and we also assume them to be constant so when replacing the variables measured with the variables that are functions of the heat equation, we also get the following equation.

$$P_{in} = \frac{m_s \cdot C_{PS} \cdot \Delta T_S}{\Delta t} + M_W \cdot C_{PW} \cdot \Delta T_W + f(P_{in}) + f(\Delta T_S) + heatloss \tag{6}$$

Replacing X1 inn the heat losses from electricity, that are the functions of energy input and replacing X2 in the heat losses due to the heat induction on the furnace wall, which is The function of the liquid steel temperature in the furnace.

$$P_{in} = \frac{m_s \cdot C_{PS} \cdot \Delta T_S}{\Delta t} + M_W \cdot C_{PW} \cdot \Delta T_W + X1 \cdot P_{in} + X2 \cdot \Delta T_S + heatloss \tag{7}$$

Putting the constants together.

$$P_{in} = \frac{\left(\frac{m_s \cdot C_{PS}}{\Delta t} + X2\right)}{(1 - X1)} \cdot \Delta T_S + \left(\frac{C_{PW}}{1 - X1}\right) \cdot M_W \cdot \Delta T_W + \left(\frac{heatloss}{1 - X1}\right) \tag{8}$$

Replacing the constant with A1, A2, and C3 so we get the following equation.

$$P_{in} = A1 \cdot \Delta T_S + A2 \cdot M_W \cdot \Delta T_W + A3 \tag{9}$$

Where

$$A1 = \frac{\left(\frac{m_S \cdot C_{PS}}{\Delta t} + X2\right)}{(1 - X1)}$$

$$A2 = \left(\frac{C_{PW}}{1 - X1}\right)$$

$$A3 = \left(\frac{heatloss}{1 - X1}\right)$$

We rearrange the equation as follows.

$$T_S = \frac{(P_{in} + A1 \cdot T_{S,i-1} - A2 \cdot M_W \cdot \Delta T_W - A3)}{A1} \tag{10}$$

Where T_S is the liquid steel temperature during the period of estimation, and $T_{S,i-1}$ is the estimated liquid steel temperature in the past time. In order to estimate the liquid steel temperature in the furnace from the heat model, it is necessary to measure the liquid steel temperature in the actual furnace for at least 1 time.

The experiment to estimate $A1, A2, A3$ is conducted by gathering the information from total processes for 4 times. During each time, we shall adjust the different energy input according to the details of each time.

The details of the calculation start from the measure of the liquid steel temperature in the furnace at the first point, and we calculate the liquid steel temperature in the furnace at the second point by replacing the electricity energy input, flow rate and temperature of cooling water and liquid steel temperature in the furnace measured during the first time, and we also assume the constant A1, A2, and A3 in equation (10). Afterwards, we calculate again and again until we get the liquid steel temperature in the furnace according to the points required in the experiment with the pattern of equation as follows.

$$T_{S,2} = \frac{(P_{in,2} + A1 \cdot T_{S,1} - A2 \cdot M_{W,2} \cdot \Delta T_{W,2} - A3)}{A1}$$

$$T_{S,3} = \frac{(P_{in,3} + A1 \cdot T_{S,2} - A2 \cdot M_{W,3} \cdot \Delta T_{W,3} - A3)}{A1}$$

$$\ldots = \ldots\ldots\ldots$$

$$\ldots = \ldots\ldots\ldots$$

$$T_{S,2200} = \frac{(P_{in,2200} + A1 \cdot T_{S,2199} - A2 \cdot M_{W,2200} \cdot \Delta T_{W,2200} - A3)}{A1}$$

Upon calculating according to the above mentioned method, we have found that the constant A1, A2, and A3 are as follows.

$$A1 = 659 \ , \ A2 = 18.4 \ , \ A3 = 100$$

Therefore, the heat model of the induction furnace shall be demonstrated in equation (11).

$$T_S = \frac{(P_{in} + 659 \cdot T_{S-1} - 18.4 \cdot M_W \cdot \Delta T_W - 100)}{659} \qquad (11)$$

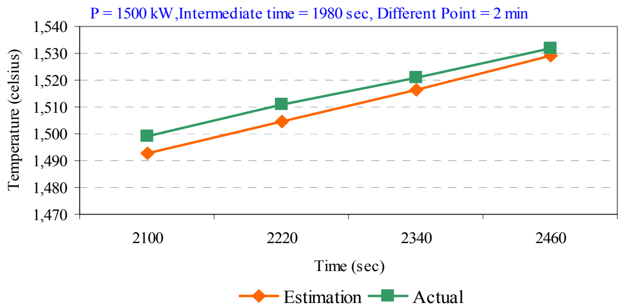
III. Experiment for the Estimation of Temperature

From the pattern of equation (11), the abovementioned heat balance equation when we realize the liquid steel temperature at the first point, we can estimate the liquid steel temperature at the next point. The sampling in the experiment takes 10 minutes and the accuracy test in the estimation of the temperature by 6 sets of tests has the details in Table 3.1.

Table 3.1: The operations of 6 sets of experiments.

Experiment 1

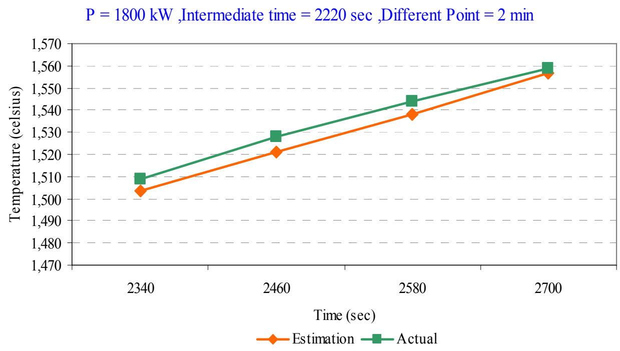
Electricity Power Input	1500	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	1980	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times



Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1493	1504	1516	1529
Liquid Steel Temperature from Measuring via Thermocouple	1499	1511	1521	1532

Experiment 2

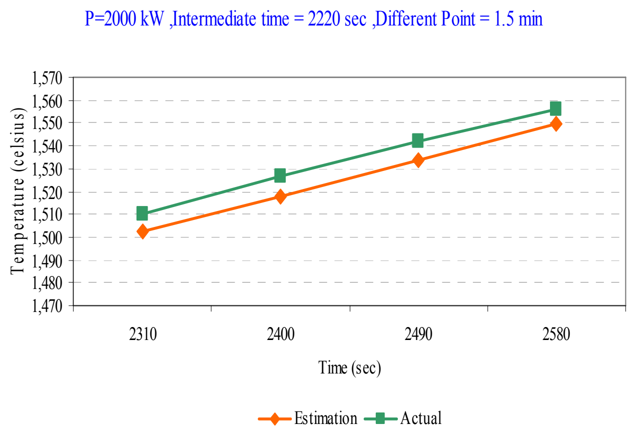
Electricity Power Input	1800	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	2220	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times



Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1504	1521	1538	1557
Liquid Steel Temperature from Measuring via Thermocouple	1509	1528	1544	1559

Experiment 3

Electricity Power Input	2000	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	2220	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times

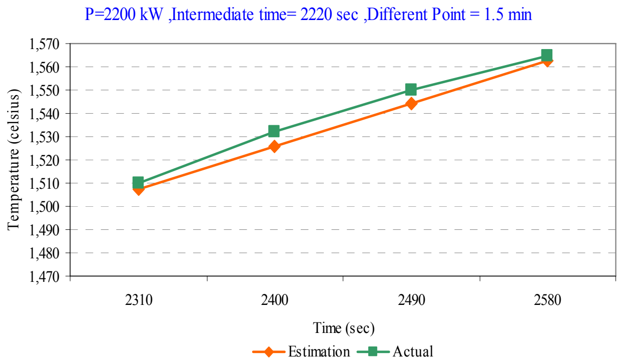


ISBN: 978-988-17012-7-5

Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1502	1518	1534	1549
Liquid Steel Temperature from Measuring via Thermocouple	1510	1527	1542	1556

Experiment 4

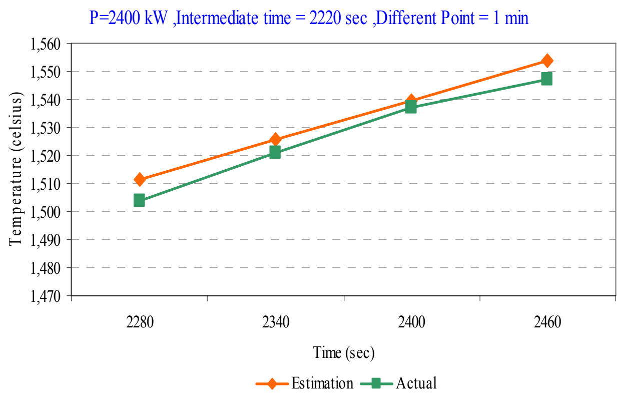
Electricity Power Input	2200	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	2220	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times



Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1505	1524	1542	1561
Liquid Steel Temperature from Measuring via Thermocouple	1510	1532	1550	1565

Experiment 5

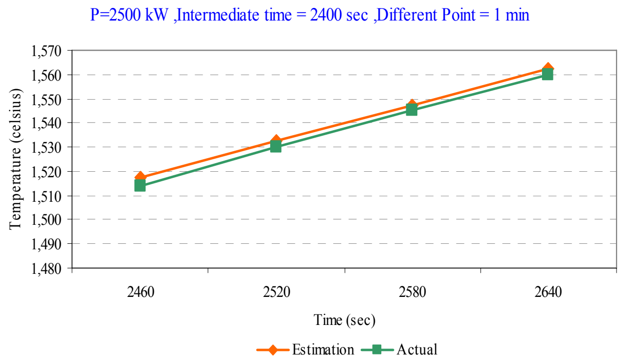
Electricity Power Input	2400	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	2220	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times



Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1511	1525	1540	1554
Liquid Steel Temperature from Measuring via Thermocouple	1504	1521	1537	1547

Experiment 6

Electricity Power Input	2500	kW
Flow Rate of Cooing Water	8.2	Kg/s
Point of First Measuring	2400	sec
Number of Times Measuring the Liquid Steel Temperature	4	Times



Point of Measuring the Temperature	1	2	3	4
Liquid Steel Temperature from Estimation	1517	1532	1547	1562
Liquid Steel Temperature from Measuring via Thermocouple	1514	1530	1545	1560

IV. Analysis of Experimental Outcome

From the 6 experiments, we conduct the experiments at different electricity power and measure the temperature in the furnace for 24 times and we have found that after finding the unrealized parameters and calculating back to predict the liquid steel temperature in order to compare with the actual temperature. We have found that both are closet to each other from the conditions of the actual operations. The maximum error is at $\pm$ 9 degree Celsius so the average is at 5.08 degree Celsius. The error of the temperature is due to the fact that $A1$ is the mass of steel multiplied by the specific heat capacity of each melting and each melting has different mixtures and the conditions of the furnace change all the time. Thus, it is difficult to control and standardize the operations of furnace in every time of operations.

V. Summary of Experiment

The experiment starts from gathering the parameters affecting the temperature in the furnace, namely, electricity power input, temperature of cooling water input – output, flow rate of cooling water. The parameter measured is calculated in the heat balance equation and tested to find the proper heat model of the furnace. Upon obtaining the heat model of the furnace, such model shall be tested to compare the accuracy of the estimation when it is actually functioned.

In the all experiment, we have found that the estimated temperature has the average error of 5.08 Degree Celsius with the maximum error of no more than $\pm$ 9 Degree Celsius.

Upon considering the error from estimated temperature and the actual temperature, we can summarize as follows.

(1) A has been changed in some experiments so the heat model has some errors.
(2) The methods used to find the unrealized parameters are simple methods so when actually applying to the furnace with complex structure and operations, the model obtained is not accurate. Thus, the estimated temperatures have some errors.
(3) The Thermocouple type R used to measure the liquid steel temperature may have some errors during the measurement. This may due to the equipment or the persons who conduct the experiments. Hence, the temperature measured may have some errors and upon estimating the temperature, the constant has some mistakes.

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