An Advanced Model for Furnace Temperature in a Reheating furnace
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Y.I.Kim,1 D.H.Kang,2 H.K.Jeong3 and K.H.Kim4

1,2,4 Energy Research Team, Research Institute of Industrial Science and Technology(RIST), Korea E-mail: yikim@rist.re.kr, kangdh@rist.re.kr, and khkim@rist.re.kr
3 Department of Hot Rolling, POSCO Kwangyang Works, Korea E-mail: shjeong@posco.co.kr

ABSTRACT

In steel works, a reheating furnace is an indispensable part of a plate/hot mill process and reheats various types of slabs to its target temperature as closely as possible with tolerable uniformity. In a conventional furnace control, the only method to predict the temperature profile of a slab and to find out a proper zone temperature(index or set-point temperature) is the mathematical model. This approach has been applied to real works on condition that it has proper physical properties and logical assumption. In this study, we make a new method of the surrounding(furnace) temperature modeling to improve the accuracy of the math model for slab temperature and a improved math model which is based on this method. In general, a previous conventional math model in plate mill plant uses the simple(linear approximation) form of measured thermocouple temperature as the surrounding temperature which is appeared at the boundary condition in model. This approach causes some meaningless coefficients in the math model, in detail, the overall heat transfer coefficient.

We carry out an experiment on proving this failure in the real furnace. After all, we make a new type of sub-model to make a more accurate gas temperature profile in the furnace. The math model based on this gas sub-model gives meaningful model parameters and reliable slab temperature profile, and moreover, this sub-model has the capability to show the influence of furnace conditions like a change of the temperature set-point, gas flow-rate. In detail, we tried the various forms of model for gas temperature like PCR(Principal Component Regression), A modified spline with gas flow-rate, elapsed time from set-point change. All tested forms give more reasonable result than previous one.

KEYWORDS
reheating furnace, slab, gas temperature modeling, PCR, Spline

INTRODUCTION

In reheating furnace, heat released by the combustion is transmitted to slab by two heat transfer mechanism. Radiation occurred between slab surface and its surroundings plays the dominant role in heat transmission and convection by flue gas contributes as minor. It is difficult to model furnace process because there are many variables such as: size of slab, steel grade, transport speed, fuel rate, furnace geometry etc. that affect these heat transfer mechanism in complicated ways. To understand how these variables affect the reheating process, it is necessary to develop a mathematical model to describe the furnace system, use the model to get quantitative information of the effect of these variables on heat transmission, and to predict the furnace performance, so as to propose the optimum control of the furnace operation and reduce the energy consumption in reheating process.

The energy consumption of the rolling process where reheating furnace is main consumer account for near 16% of the total energy consumed at a whole steel work. Therefore, there have been various researches about the reheating furnace process, and those works are categorized into the modeling of heat
transfer phenomena within the furnace for the purpose of a better furnace description (B.Y. Yang 1995, Dag Lidholm and Bo Leden 1999, Naoharu Yoshitani 1991) and its online implementations on the reheating process control to reduce energy cost (Fred Shenvar 1994, Yoshihiko Misaka et al. 1982).

The structure of furnace is complicated and the operation condition varies widely, a simple analysis is not good enough to evaluate the furnace performance. Thus, in papers related with furnace heat transfer modeling, main issue is to make precise mathematical models about the heat transfer mechanism between slab and its surroundings to predict the discharged slab temperature with better accuracy. Although CFD studies give more and more improved results about fluid dynamics in furnace, these results are less applied to real furnace industry directly as its complexity and execution time limit. So, conventional heat transfer model for reheating furnace is based on the concept of “furnace temperature”, uses a math model based on only radiation heat transfer and derives an “overall heat exchange factor” from empirical data to estimate the heat flow transmitted to slab. This method can get good prediction results when furnace temperature is stable and the operation condition is similar to previous experiment.

In this paper, we focus on more accurate math model with improved furnace temperature. It seems that there is no extensive studies and discussion on this topic. In general, constant or linear temperature profile has been assumed as characteristic temperature for the given section of furnace. One dimensional heat transfer model for slab with the overall heat exchange factor is used as comparative reference and the some types of gas temperature sub-model are tried to improve the slab temperature prediction model performance.

THEORY

SLAB CONDUCTION MODEL

For a rectangular slab of steel that is exposed to a hot furnace environmental, the non-stationary temperature distribution is obtained from the three-dimensional time-dependent heat-conductivity equation. During the reheating of slab, the horizontal temperature gradients within the steel in the direction along the furnace are small which is compared with the vertical temperature gradients. Therefore the horizontal temperature gradients can be neglected, then the heat equation becomes:

\[ \rho(T)C_p(T) \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k(T) \frac{\partial T}{\partial x} \right) \]

where, \( \rho \) (density), \( C_p \) (heat capacity), and \( k \) (heat conductivity) have a functional form with respect to temperature for a specified slab. Equation(1) is discretized by means of a finite volume method (FVM) which is formulized and employed by Suhas V. Patankar (1965). For boundary conditions, wall refractory radiation and gas radiation are considered which give the following boundary condition.

\[ q = -k \frac{\partial T}{\partial n} = q_{gs} + q_{ws} \]

Where \( q \) is the heat transfer rate (heat flux), \( n \) means the normal direction of the slab surface, \( q_{gs} \) is the heat flux from gas volume to slab surface, \( q_{ws} \) from wall to slab surface. Non-luminous gas radiation comes from the combustion product of heteropolar gases such as: CO\textsubscript{2}, H\textsubscript{2}O, SO\textsubscript{2}. In practical case, the furnace atmosphere contains mainly N\textsubscript{2}, CO\textsubscript{2}, and H\textsubscript{2}O, the radiating power of N\textsubscript{2} is negligible compared with CO\textsubscript{2} and H\textsubscript{2}O. Therefore the radiating power of CO\textsubscript{2} and H\textsubscript{2}O is counted only in reheating furnace. The net radiation heat exchange between a gas volume and a slab surface is given by:

\[ q_{gs} = \frac{\sigma \varepsilon_s}{[1-(1-\varepsilon_s)(1-A_{gs})]} (\varepsilon_s T_g^4 - A_{gs} T_s^4) \]
The gas emissivity ($\varepsilon_g$) and the gas absorptivity ($A_g$) are calculated as a function of gas temperature, slab surface temperature, gas layer thickness, and partial pressure of CO$_2$, H$_2$O. Total emissivity and absorptivity of gas mixture are modeled as F.R. Steward and Leckner (1972):

$$\varepsilon_g = (\varepsilon_{g_{CO_2}} + \varepsilon_{g_{H_2O}}) \quad \text{and} \quad A_g = [(T_{g}/T_s)^{0.65} \varepsilon_{g_{CO_2}} + (T_{g}/T_s)^{0.45} \varepsilon_{g_{H_2O}}]$$

(4)

The radiative heat transfer rate from wall to the slab surface is given by:

$$q_{sw} = \sigma(\varepsilon_w\varepsilon_{gm} F_{sw} + \Delta \varepsilon_f)(T_w^4 - T_s^4) \quad \varepsilon_f$$

(5)

Where $\Delta \varepsilon_f$ is a correction factor for flame radiation, $F_{sw}$ is a geometry view factor and the mean transmissivity ($\tau_{gm}$) of the gas.

**Principal Component Regression**

The principal component regression (PCR) is based on the multiple linear regression (MLR) and principal component analysis (PCA) (Svante Wold et al. 1987, Paul Geladi 1986). PCA is a method of writing a data matrix $X$ of rank $r$ as a sum of $r$ matrices of rank 1:

$$X = M_1 + M_2 + \cdots + M_r$$

(6)

These rank 1 matrices, $M_h$, can be written as outer products of two vectors, a score $t_h$ and a loading $p_h^t$:

$$X = t_h p_h^t + t_2 p_2^t + \cdots + t_r p_r^t$$

(7)

Generally, one wants an operator that projects the columns of $X$ onto a single dimension and an operator that projects the rows of $X$ onto a single dimension (see Figure 1.). In the first case, each column of $X$ is represented by a scalar; in the second case, each row of $X$ is represented by a scalar. It will be shown that these operators are of a simple nature.

Nonlinear iterative partial least squares (NIPALS) does not calculate all the principal components at once. It calculates $t_1$ and $p_1^t$ from the $X$ matrix. Then the outer product, $t_1 p_1^t$, is subtracted from $X$ and the residual $E_1$ is calculated. This residual can be used to calculate $t_2$ and $p_2^t$:

$$E_1 = X - t_1 p_1^t, \quad E_2 = E_1 - t_2 p_2^t, \cdots, \quad E_h = E_{h-1} - t_h p_h^t, \cdots, \quad E_m = E_{m-1} - t_m p_m^t$$

(8)

At finally, PCR is described by the results from above PCA which be used to explain the principal component transformation of a data matrix $X$. This is a representation of $X$ as its scores matrix $T$. The transformation is $T = XP$. So now the MLR formula can be written as $Y = TB + E$ and the regression coefficient matrix is given as $B = (T^T)^{-1}T^T Y$.

In implementation, this basic form is extended to hold serial data as Dynamic PCR (DPCR). The first form of DPCR is finite impulse response (FIR) as following when there are one dependent and one independent variables,

$$y(t) = a_0 x(t) + a_1 x(t-1) + \cdots + a_l x(t-l)$$

(9)

If the system is multivariate as our case, then the data matrix $X$ should have next one.

$$X_{FIR} = [X(t) X(t-1) \ldots X(t-l)]$$

(10)

An other form of DPCR is auto regressive model with exogenous input (ARX) that has following:
\[
    y(t) = b_1 y(t-1) + b_2 y(t-2) + \ldots + b_{m_y} y(t-m) + \\
    a_0 x(t) + a_1 x(t-1) + \ldots + a_l x(t-l)
\]

In this case, the data matrix has \( X_{RX} = [Y(t-1) Y(t-2) \ldots Y(t-m) X_{FIR}] \) form.

**CUBIC SPLINE**

The most common piecewise polynomial approximation using cubic polynomials between each successive pair of nodes is called “cubic spline interpolation.” A general cubic polynomial involves four constants; so there is sufficient flexibility in the cubic spline procedure to ensure not only that the interpolant is continuously differentiable on the interval, but also that it has a continuous second derivative on the interval.

**APPLICATION AND RESULTS**

**EXPERIMENTS**

We apply previous theories to various gas sub-models and test these models on real furnace. First of all, temperature of flue gas is measured to evaluate sub-models as following:

1) A test slab is prepared as Figure 2 that have caved-holes to be equipped with thermocouples(T/C): the thermocouple named as ‘BENEATH’ is used to measure the temperature of flue gas that is lower-part of furnace and it is positioned at 100~250mm beneath the slab bottom surface, ‘ABOVE’ is for upper-part at 100~250m above, and the others for inner points of slab(30,110,190mm) where each three of them is used to track the temperature of skid, non-skid, and edge part of slab respectively.

![Figure 2. Specification of test slab used for temperature measurement](image)

2) It is charged to the target furnace of which gas temperature will be modeled (Figure 3.)

![Figure 3. Schematic drawing of general furnace](image)
3) The following logged data chart (see Figure 4, the legend ‘NSKD’ represents the non-skid part of a slab which is depicted at Figure 2 and ‘BOT/MID/TOP’ means the bottom(222mm), middle(120mm), top(20mm) position of depth direction) obtained from slab temperature measuring experiment is used as basic data for furnace temperature modeling.

We have an interest in gas temperatures that are depicted at Figure 4(RT_ABOVE/BENEATH) and modeling these as a function of other measured variables(fuel-rate, temperatures of control-T/C, pressure and slab position).

[Image of Figure 4. Typical temperature profile measured from experiments]

PCR RESULTS
PCR type-models are evaluated by using the sampled data with “ABOVE” temperature. All data are mean-centered and scaled for PCR and X data block is composed of $[G \times 4, A \times 4, TC \times 4, P \times 2, pos]$ where G as fuel flow-rate, A as air flow-rate, TC as temperature of thermocouple which is measured and used to control, P as Pressure(two measuring points in this case) and pos as slab position. The results of various PCR models are shown in figure 5.

[Images of PCR results showing various models]

Figure 5. Sample Results of PCR models
In figure 5, the values of axis are the mean($\bar{T}$)-centered and standard deviation($\sigma$)-scaled temperatures($T' = (T - \bar{T})/\sigma$) except the x-axis of 5-d). Figure 5-d) shows prediction result with ARX model with only 15 PCs with respect to ‘BENEATH’ temperature (this is used to evaluate the model on the assumption that it shows similar trend in temperature). But its error graph reveals that this model is not good enough to be used in on-line as it has incline in error which can be removed if sufficient data are available and peak values in some regions.

**CUBIC SPLINE RESULTS**

Cubic spline approximation is tried to overcome defects of PCR models. Furnace shown in Figure 6 is used for this method as target because experiment is taken on it. To make spline curve of furnace temperature, it should has an optimal knots points and initial positions as Figure 6.

![Figure 6. Schematic drawing of a furnace used for evaluating the spline method.](image)

At figure 6, knots are depictured as a filled circle and real thermocouples as a filled small rectangle with the mark(×2/4) means that there are 2/4 thermocouples at same longitudinal direction with different depth into the paper. At this work, we introduced, for fast practical application, an imaginary temperature as independent variable that is a function of various measured variables. Making a imaginary temperature requires optimization technique and its flow chart is shown in Figure 7, where experiment step is same as previous one and optimization is agreed with most common steps (Nedler and Mead’s simplex method is used with penalty on boundary).

<table>
<thead>
<tr>
<th><strong>Interpolant determination steps</strong></th>
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<tbody>
<tr>
<td>STEP 1. Experiment step</td>
</tr>
<tr>
<td>1.1 Prepare the test slab</td>
</tr>
<tr>
<td>1.2 Measure the slab inner/near temperature</td>
</tr>
<tr>
<td>1.3 Log the furnace operation data</td>
</tr>
<tr>
<td>(Control T/C, Gas flow-rate, Pressure,…)</td>
</tr>
<tr>
<td>STEP 2. Optimization Step</td>
</tr>
<tr>
<td>2.1 Guess Initial value for fitting parameters</td>
</tr>
<tr>
<td>2.2 Simulate the furnace operation as real case</td>
</tr>
<tr>
<td>2.3 Check performance Index</td>
</tr>
<tr>
<td>(Error function of $T_m$ &amp; $T_p$)</td>
</tr>
<tr>
<td>2.4 Repeat the step 2,2 with new value</td>
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</tbody>
</table>

If we use the thermocouple data only, then there are four available temperature samples which can be used as independent variable in longitudinal direction at specific time (see Figure 6 marked as grayed rectangle for each upper and lower part of furnace) in raw data. Thus, as previously mentioned we assume that temperatures for knots are guessed as following:

$$T_i^I = \alpha_i T_i^R + \beta_i G_i^R + \gamma_i$$  (12)

where, $T_i^I, T_i^R$ mean imaginary and real control-T/C temperature respectively, $G$ means gas flow-rate and $\alpha, \beta$ are fitting parameters that are determined from optimization step. In detail, the optimization steps are:

1) guess the intial values for $\alpha, \beta, \gamma$
2) calculate imaginary temperature for Knots with equation 12
3) calculate interpolant coefficients
4) compare these approximated temperature with the measured sample data for all sample positions.
5) repeat above steps until to converged with the given tolerance.

The final values of parameters are tabled in Table 1 for above furnace temperature.
Table 1. Results of fitting parameter for imaginary temperature, where POS has mm unit

<table>
<thead>
<tr>
<th>POS</th>
<th>α</th>
<th>β</th>
<th>γ</th>
</tr>
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<tbody>
<tr>
<td>00000</td>
<td>1.102</td>
<td>0.0021</td>
<td>-118.537</td>
</tr>
<tr>
<td>08480</td>
<td>1.001</td>
<td>-0.0024</td>
<td>-51.0798</td>
</tr>
<tr>
<td>13640</td>
<td>1.037</td>
<td>-0.0005</td>
<td>-66.5595</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>39910</td>
<td>1.0</td>
<td>0.00016</td>
<td>-21.3166</td>
</tr>
<tr>
<td>42700</td>
<td>1.0</td>
<td>0.0001</td>
<td>-2.537</td>
</tr>
</tbody>
</table>

Linear and spline approximation results are compared in Figure 8. It can be seen that spline method is superior in its accuracy to linear.

The next figure is typical prediction result of slab temperature with spline approximation. It shows good accuracy on slab and furnace temperature. In figure, ‘NP’ and ‘NM’ represent the predicted and measured slab temperature for each depth position(‘B’ottom, ‘C’enter, ‘T’op), ‘RP’ and ‘RM’ are furnace temperatures in a similar vein.
DISCUSSION

New types of gas sub-model are evaluated to give better prediction result of slab temperature and more precise math model which describes furnace temperature as realistic. In this work, we showed investigable issue on reheat furnace modeling and control problem. Although this approach improves the accuracy of math model, it seems that there are some defects to be reformed in future work. As example, it has no support on long term temperature declines when stand-still is occurred

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