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Evaluation of Optimal Residence Time in a Hot Rolled Reheating Furnace

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***Abstract*—**To calculate the temperature distribution of the slab in a hot rolled reheating furnace a mathematical model has been developed by considering the thermal radiation in the furnace and transient conduction in the slab. The furnace is modeled as radiating medium with spatially varying temperature. Radiative heat flux within the furnace including the effect of furnace walls, combustion gases, skid beams and buttons is calculated using the FVM and is applied as the boundary condition of the transient conduction equation of the slab. After determining the slab emissivity by comparison between simulation and experimental work, variation of heating characteristics in the slab is investigated in the case of changing furnace temperature with various time and the slab residence time is optimized with this evaluation.

***Keywords*—**Reheating Furnace, Thermal Radiation, Residence Time, FVM for Radiation

I. Introduction

THE reheating process is commonly used to raise the temperature of the slabs so that the subsequent hot-rolling process runs on wheels. Since the reheating process should have lower energy consumption and combustion-generated pollutant emissions, the transient analysis of the slab in the reheating furnace has attracted a great deal of interest during the past few decades. Furthermore, because the attainment of uniform temperature distributions inside the slab and the target temperature of the slab at the furnace exit determine the quality and productivity of the steel product, the reheating furnace process must be analyzed accurately and rapidly.

These analytical studies can be classified into following two categories. The first one is to solve the full Navier-Stokes and energy conservation equations governing the hot gas flow and combustion process in the furnace as in [1], and the second method, [2]-[4], which is simple but can reasonably simulate the thermal behavior of the slab, focuses on the analysis of the radiative heat transfer in the furnace and the transient heat conduction within the slab.

In this work, the total heat flux including radiative and convective heat flux is calculated in the furnace gas field, and then the heat conduction analysis of the slab is performed by applying the total heat flux as the boundary condition of the transient heat conduction equation, which can be categorized as the second approach. The furnace is modeled as radiating medium with spatially varying temperature and is filled with hot combustion gases that consist of H_2O, CO_2, O_2, and N_2, and have highly spectral radiative characteristics. Accordingly, the WSGGM by [5] is used to consider the nongray behavior of the combustion gases. In the following sections, after describing the methodology adopted here, variation of heating characteristics in the slab is investigated with the residence time and the slab residence time is optimized in the case of changing furnace temperature.

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II. Mathematical Model

A. Governing Equations

The two dimensional transient heat conduction equation to predict the temperature distribution within the slab is,

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\kappa \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\kappa \frac{\partial T}{\partial y}\right) \tag{1}$$

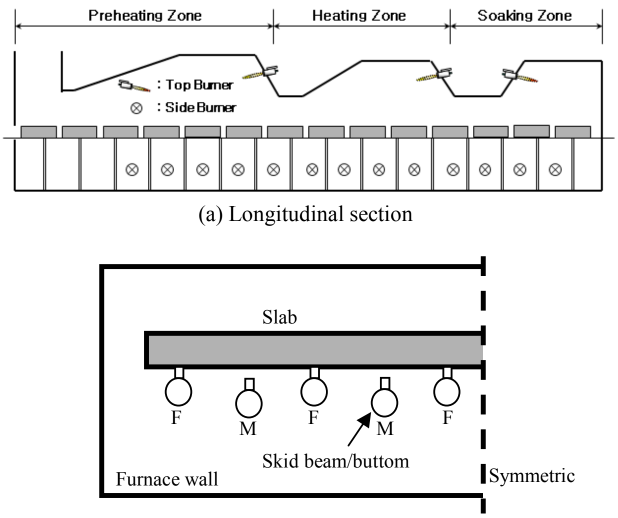
where, ρ, C and κ represent density, specific heat, and conductivity of the slab, respectively. The boundary condition of (1) is the total heat flux on the slab surface, which can be obtained from the summation of the convective and radiative heat flux as following,

$$q_{slab}^{T} = q_{slab}^{C} + q_{slab}^{R} \tag{2}$$

The convective heat transfer between the furnace gas and the solid surface is evaluated by using the equation,

$$q_{slab}^{C} = H_c (T_g - T_{slab}) \tag{3}$$

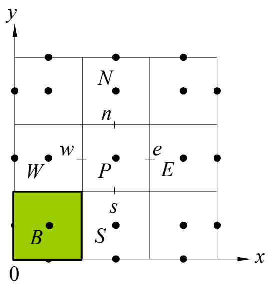
where H_c is the gas convective heat transfer coefficient at the surface of the slab of 7.8 W/m^2K, where coke-oven gases are used as fuel.



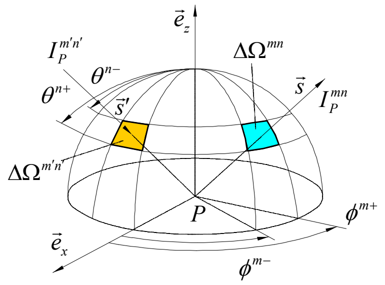
(a) Longitudinal section

(b) Transverse section

Fig. 1 Geometry of a reheating furnace



(a) Control volume



(b) Control angle

Fig. 2 Spatial control volume and control(solid) angle

The radiative heat flux on the slab surface is calculated from the following equation,

$$q^{R}_{slab} = \int_{\Omega=4\pi} I(\vec{r}_w, \vec{s})(\vec{s}\cdot\vec{n}_w)d\Omega \tag{4}$$

where $I(\vec{r}_w, \vec{s})$ is the radiation intensity at the slab surface $\vec{r}_w$ and directions $\vec{s}$, $\vec{n}_w$ is the outward unit normal vector at the slab surface, and Ω is the solid angle. The transient heat conduction equation expressed in (1) is discretized by using the finite volume method. The radiative transfer equation (RTE) must be analyzed in order to compute the radiative heat flux on the slab surface as shown in (4). In this work, the FVM for radiation is adopted to discretize the RTE as in [6] and [7].

B. Analysis Conditions

The walking-beam type reheating furnace modeled in this work is shown in Fig. 1. This furnace has about 35 m in length and 11 m in width, and the highest furnace roof is 5 m inside. The fixed and moving skids are arranged in the furnace as shown in Fig. 1 (b), and the slabs are supported and moved in the furnace by the fixed and moving beams, respectively. Namely, after the slab is supported and heated on the fixed skids for a certain time, it is moved on the next fixed beam by the cyclic movement of the moving skids, which consists of sequential upward, forward, downward, and then backward movements.

The slab is a high carbon steel, whose carbon content is 0.35~0.55 % and the themophysical properties are given in TABLE I. The slab is 0.25 m in height and 8.7 m in length and is assumed to be isothermal of 300K when charged into the furnace. Emissivities of the slab and other walls are set to 0.5 and 0.75, respectively

Although the temperatures of the gases within a real furnace vary according to conditions of combustion and flow at each location, two types of the mean temperature at each zone, listed in TABLE II, are used where To = 1100℃. Mass fraction of H_2O, CO_2, O_2, and N_2 based on experimental data is 0.111, 0.177, 0.015 and 0.697, respectively. Because of its symmetry, a half of the furnace in the transverse direction is modeled and the spatial mesh systems used in this study is $N_x = 179$, $N_y = 71$ and angular systems of $(N_\theta \times N_\phi) = (4\times12)$ for 2π sr.

TABLE I
THERMAL PROPERTIES OF SLAB

Temperature (℃)	Conductivity (W/mK)	Specific Heat (J/kgK)	Density (kg/m^3)
30	26.89	299.0	
400	25.44	401.6	
600	22.70	512.0	7778
800	20.89	542.8	
1000	23.69	478.9	

TABLE II
PATTERNS OF FURNACE TEMPERATURE

ZONE	Old-pattern		New-pattern	
	Tg_upper	Tg_lower	Tg_upper	Tg_lower
Preheating	To	To	To+20	To+20
Heating	To+110	To+90	To+130	To+120
Soaking	To+100	To+80	To+110	To+100

III. RESULTS AND DISCUSSION

A. Model Validation

In order to validate the model developed, the results from the present model are compared with the experimental data provided by POSCO. The slab used is 1.1 m in width, 0.2 m in height, 8.3 m in length and the slab residence time is 179 min.

Fig. 3 shows the computed centerline and upper surface temperature of the slab compared with the measured data and a reasonably good agreement is observed between them. At the furnace exit, the temperature difference of the slab surface is within 1 % and the centerline is within 0.5 %.

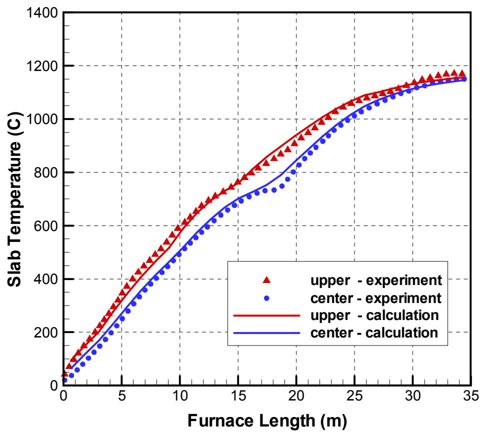
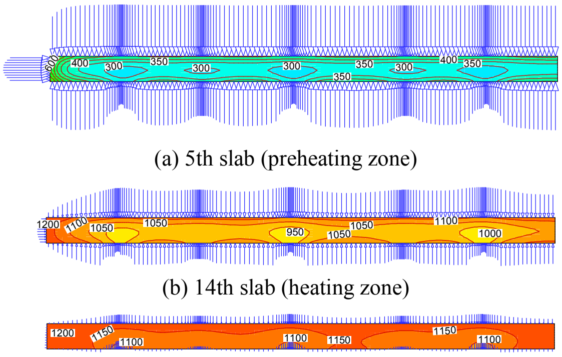


Fig. 3 Comparison between simulation and experiment



(a) 5th slab (preheating zone)

(b) 14th slab (heating zone)

(c)29th slab (soaking zone)

Fig. 4 Radiative heat flux on the slab surfaces and temperature distribution of the slab

Fig. 4 shows the heat flux distribution on the slab surface and the temperature distribution inside the slab in each zone of the furnace. It can be seen from the figure that a large amount of heat energy is transferred to the slab in the preheating zone because of the relatively high temperature difference between the slab and the surrounding combustion gases, and then, temperature of the slab is sharply increased. However due to the heating characteristics of the slab in which the heat is transferred from the slab surface to the inside by conduction after the slab surface is firstly heated from the surroundings by radiation and convection, there is a considerable temperature difference between the surface and the inside of the slab. Slabs are further heated as they pass through the subsequent heating and soaking zone, and the temperature gradient within the slab becomes smaller.

The existing skid structures make the heat flux depressed around the slab and skid contact region due to the shielding effect of the skid, and thereby, the temperature of the slab in this region is relatively low as shown in Fig. 4. Also, it even affects the temperature distribution of the top surface of the slab, and therefore, the heat flux on the top surface of the slab is rather slightly increased in this region as shown in Fig. 4.

B. Heating Characteristics of Old-pattern

First, computations have been carried out with the condition of furnace temperature named Old-pattern in TABLE II and Fig. 5 represents the variation of slab mean temperature with the residence time. As shown, temperature of the slab increases with residence time but the amount of temperature change is on the decrease at the same interval of time increment.

Heating characteristics of the slab are summarized with the residence time and shown in Fig. 6. In contrast to furnace exit temperature of the slab, temperature difference between surface and center of the slab and skidmark decrease with residence time. Skidmarks are the longitudinal temperature defferences in the regions of slabs close to the skids, and if severe, give rise to defects in the thickness. From Fig. 6, we can predict the slab exit temperature, heat uniformity inside the slab and skidmark at a given residence time.

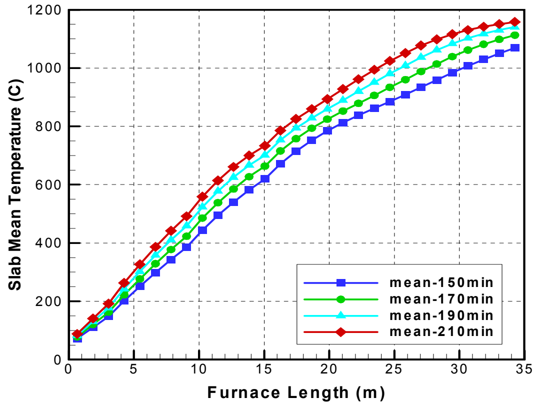


Fig. 5 Variation of slab mean temperature with the residence time in case of Old-pattern

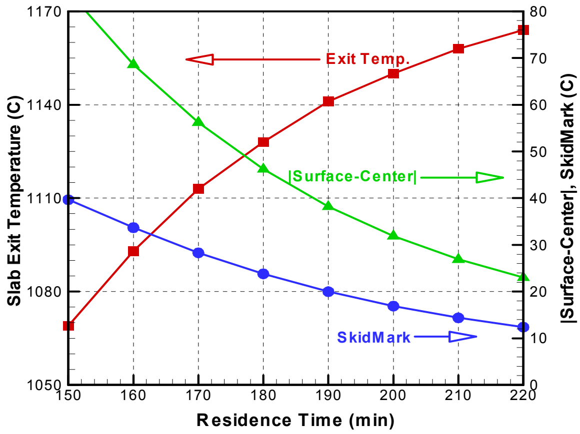


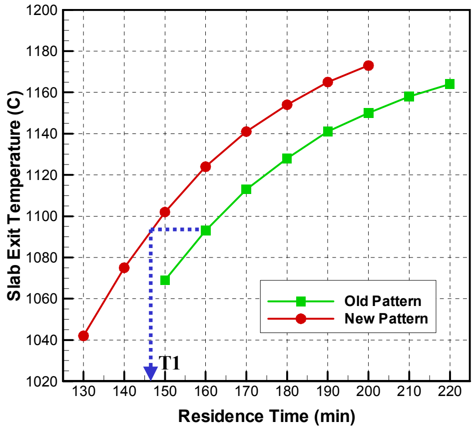
Fig. 6 Heating characteristics with the residence time in case of Old-pattern

C. Optimal Residence Time of New-pattern

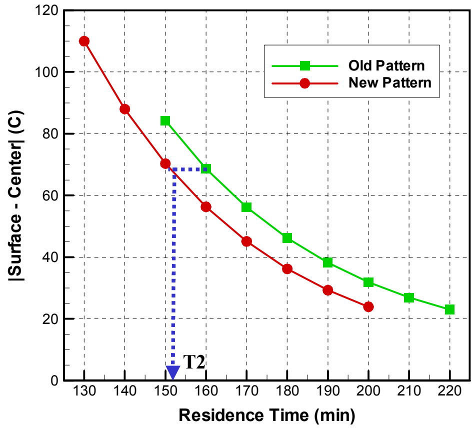
In the case of increased furnace temperature (New-pattern in TABLE II) to achieve high production rates, we simulated the slab heating characteristics with residence time varying from 130 min to 200 min and the results are compared with those of Old-pattern to obtain optimal residence time of the slab.

The resulting slab temperature curve at the furnace exit for New-pattern compared with that for Old-pattern is shown in Fig. 7 (a). If we suppose that the slab residence time is 160 minute for Old-pattern, slab exit temperature for New-pattern should be the same to or higher than that for Old-pattern at 160minute, so the residence time must be more than T1 in Fig. 7 (a).

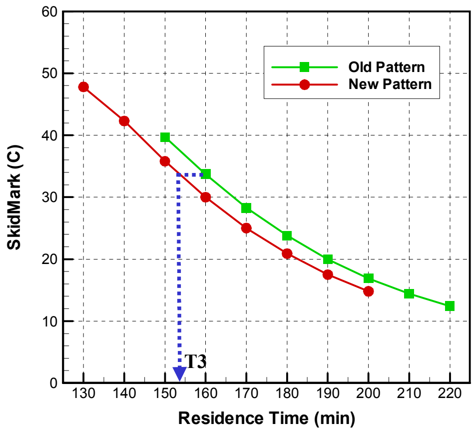
Similary, because the temperature difference between surface and center of the slab and skidmark for New-pattern should not exceed the values for Old-pattern at that residence time, the residence time for New-pattern condition must be also more than T2 and T3, respectively in Fig. 7 (b), (c). Therefore, if the furnace temperature condition of New-pattern is applied instead of Old-pattern, optimum residence time which can minimize change of slab heating characteristics by time contraction will be maximum value of T1 and T2 and T3.



(a) Slab temperature at the furnace exit



(b) Temperature uniformity inside the slab



(c) Skidmark

Fig. 7 Comparison of slab heating characteristics between the two different patterns of furnace temperature

IV. Conclusion

In this work, a mathematical model for a slab reheating furnace has been developed and applied to determine slab residence time by comparing the heating characteristics of the slab when the furnace temperature is changed. Slab residence time in the furnace is closely related to energy consumption and pollutant emissions, so it is important to find the optimal residence time at given conditions. Although the numerical results were for a specific example under consideration, the same methodology may be used to model any similar reheating furnace and to evaluate optimum residence time of the slab in case of changing operation conditions such as slab size, furnace temperature, etc.

References

[1] J. G. Kim, K. Y. Huh, I. T. Kim, "Three-Dimensional Analysis of the Walking-Beam-Type Slab Reheating Furnace in Hot Strip Mills," *Numer. Heat Transfer, Part A*, vol. 38, pp. 589-609, 2000.

[2] Z. Li, P. V. Barr, J. K. Brimacombe, "Brimacombe, Computer Simulation of the Slab Reheating Furnace", *Can. Metall. Quarterly*, vol. 27, pp. 187-196, 1998.

[3] B. Y. Yang, C. Y. Wu, C. J. Ho, T.-Y. Ho, "A Heat Transfer Model for Skidmark Formation on Slab in a Reheating Furnace", *J. Mater. Process. Manufactur. Sci.*, vol. 3, pp. 277-295, 1995.

[4] M. Y. Kim, "A Heat Transfer Model for the Analysis of Transient Heating of the Slab in a Direct-Fired Walking Beam Type Reheating Furnace", *Int. J. Heat and Mass Transfer*, vol. 50, pp. 3740-3748, 2007.

[5] T. F. Smith, Z. F. Shen, J. N. Friedman, "Evaluation of coefficients for the weighted sum of gray gases model",ASME *J. Heat Transfer*, vol. 104, pp. 602-608, 1982.

[6] S. W. Baek, M. Y. Kim, J. S. Kim, "Nonorthogonal Finte-Volume Solutions of Radiative Heat Transfer in a Three-Dimensional Enclosure," *Numer. Heat Transfer, Part B*, vol. 34, pp. 419-437, 1998.

[7] D. Y. Byun, S. W. Baek, M. Y. Kim, "Investigation of Radiative Heat Transfer in Complex Geometries using Blocked-Off, Multiblock, and Embedded Boundary Treatments," *Numerical Heat Transfer, Part A*, Vol. 43, pp. 807~825, 2003