1. Introduction

Iron must go through a series of thermal and mechanical processes before it can be used as useful industrial resource. These processes are divided into roughly four steps; the iron making process, the steel making process, the continuous casting process, and the hot rolling process. Among the four processes, the reheating furnace process is the midway step between the continuous casting process and the hot rolling process and is commonly used to raise the temperature of the slab to enhance plasticity of the slab for the subsequent hot rolling process. Since the furnace process should have lower energy consumption and pollutant emissions, the analysis of transient heating characteristics 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 furnace process must be analyzed accurately and rapidly. However, experimental approach for analyzing a real reheating furnace process is greatly limited by the complex three dimensional structures and their influence on the furnace process. Therefore, models and methods to predict the furnace combustion and heat transfer processes are in high demand, because they can be used to accurately and rapidly investigate the reheating furnace.

Meanwhile, the foregoing numerical studies can be classified into two categories. The first category of numerical studies solves the full Navier–Stokes and energy conservation equations governing the hot gas flow and combustion process in a furnace, where the thermal radiation acts as an energy source term via the divergence of radiative heat flux. Kim et al. performed these three dimensional CFD analysis by considering the turbulent reactive flow and radiative heat transfer in the walking-beam type slab reheating furnace. They used the commercial FLUENT code, and predicted the temperature distribution in the furnace and the heat fluxes through the upper and lower surfaces of the slabs. Kim and Huh conducted a similar analysis and calculated the steady state heat transfer to slabs and performed separate calculation to obtain the temperature distribution in a slab by using the finite difference method. Although these full CFD analyses make it possible to accurately predict the thermal and combusting fluid characteristics in the furnace, they necessitate long computational time and resulting much cost because of such difficulties as the treatment of so many governing equations and the complexity of the furnace structure as well as the uncertainty of the models. The second method, 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. Li et al. developed the mathematical model for predicting the steady state heat transfer to slabs and performed separate calculation to obtain the temperature distribution in a slab by using the finite difference method. Although these full CFD analyses make it possible to accurately predict the thermal and combusting fluid characteristics in the furnace, they necessitate long computational time and resulting much cost because of such difficulties as the treatment of so many governing equations and the complexity of the furnace structure as well as the uncertainty of the models. The second method, 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. Li et al. developed the mathematical model for predicting the steady state heat transfer to slabs and performed separate calculation to obtain the temperature distribution in a slab by using the finite difference method. Although these full CFD analyses make it possible to accurately predict the thermal and combusting fluid characteristics in the furnace, they necessitate long computational time and resulting much cost because of such difficulties as the treatment of so many governing equations and the complexity of the furnace structure as well as the uncertainty of the models. The second method, 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. Li et al. developed the mathematical model for predicting the steady state heat transfer to slabs and performed separate calculation to obtain the temperature distribution in a slab by using the finite difference method. Although these full CFD analyses make it possible to accurately predict the thermal and combusting fluid characteristics in the furnace, they necessitate long computational time and resulting much cost because of such difficulties as the treatment of so many governing equations and the complexity of the furnace structure as well as the uncertainty of the models.

In this work, a mathematical heat transfer model of a walking-beam type reheating furnace has been developed. The model can predict the heat flux distribution within the furnace and the temperature distribution in the slab throughout the reheating furnace process by considering the heat exchange between the slab and its surroundings in the furnace, including the radiant heat transfer among the slabs, the skids, the hot gases and the furnace wall as well as the gas convection heat transfer in the furnace. The furnace filled with hot combustion gases such as H2O, CO2, O2, and N2 is modeled as radiating medium with spatially varying temperature. After the predictions of the present model were compared with the data from an in situ measurement in the furnace, the effect of the skids on the slab heating, the heat transfer characteristics and temperature behavior of the slab were investigated by changing such parameters as residence time and emissivities of the slab and the furnace wall.

KEY WORDS: reheating furnace; steel slab heating; radiative heat flux; convective heat flux; skid mark formation; finite volume method.
considering the quasi-steady two dimensional heat transfer transverse to the marching direction of the slab in the reheating furnace. Recently, Kim5) developed a heat transfer model to predict the transient heating of the slab in a direct-fired walking-beam type reheating furnace by considering thermal radiation. This model is simple and accurate but requires less computational time than the first approach.

In the work, a mathematical heat transfer model is suggested in order to predict the heat flux impinging on the slab surface and thereby temperature distribution inside the slab, which can be categorized as the second approach. In other words, firstly, the total heat flux including radiative and convective heat flux is calculated in the furnace gas field by using the experimental data related to the temperature and concentration distributions of the furnace gas as well as the temperature distribution of the furnace wall, 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. Therefore, the model can predict the thermal behavior of the slab throughout the furnace.

The furnace in this paper is modeled as radiating medium with spatially varying temperature and is filled with hot combustion gases that consist of H₂O, CO₂, O₂, and N₂, and have highly spectral radiative characteristics. Accordingly, the weighted sum of gray gas model (WSGGM)6) is used to consider the nongray behavior of the combustion gases. In the following sections, after describing the methodology adopted here for the prediction of furnace processes within the reheating furnace, the effects of such parameters as the furnace charging speed (or residence time) and emissivities of the slab and furnace wall on the heat transfer characteristics and thermal behavior of the slab are investigated. Finally, some concluding remarks are given.

2. Description of the Mathematical Model
2.1. Structure of the Walking-beam Type Reheating Furnace

The walking-beam type reheating furnace modeled in this work is shown in Fig. 1. This furnace, currently run in the steel industry, has about 35 m in length and 11 m in width, and the highest furnace roof is about 5 m inside. There are five zones in the reheating furnace as shown in Fig. 1(a); non-firing zone, charging zone, preheating zone, heating zone, and soaking zone. 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%. The slab is 1.1 m in width, 0.23 m in height and 8 m in length. There are twenty-nine slabs with 0.1 m interval between them in the reheating furnace. The slab is assumed to be isothermal of 26.8°C when charged into the furnace and its thermophysical properties are given in Table 1. Those values shown Table 1 is obtained from the POSCO technical R&D center. Although the temperatures and the concentration distributions of the gases within a real furnace vary according to conditions of combustion and flow at each location, the mean temperature and mean mass fraction based on experimental data, listed in Tables 2 and 3, respectively, is used in this work. Furthermore, the temperatures of the furnace wall and skids used are listed in

![Fig. 1. Geometry of the reheating furnace: (a) longitudinal and (b) transverse sections.](image-url)
Table 1. Conductivity and specific heat of the slab.

| Temperature [°C] | Conductivity [W/mK] | Specific Heat [J/kgK] |
|------------------|----------------------|-----------------------|
| 30               | 26.89                | 299.0                 |
| 400              | 25.44                | 401.6                 |
| 600              | 22.70                | 512.0                 |
| 800              | 20.89                | 542.8                 |
| 1000             | 23.69                | 478.9                 |

Table 2. Temperature conditions used in this work [°C].

| Zone       | $T_s$ Upper | $T_s$ Lower | $T_w$ Upper | $T_w$ Lower | $T_{sw}$ |
|------------|-------------|-------------|-------------|-------------|----------|
| Non-firing | 950         | 950         | 950         | 950         | 750      |
| Charging   | 1150        | 1150        | 1150        | 1150        | 1050     |
| Preheating | 1240        | 1240        | 1240        | 1240        | 1140     |
| Heating    | 1250        | 1230        | 1250        | 1230        | 1130     |
| Seaking    | 1160        | 1120        | 1160        | 1120        | 1020     |

Table 3. Mass fractions of the furnace gases.

| Furnace gas | $H_2O$ | $CO_2$ | $O_2$ | $N_2$ |
|-------------|-------|--------|-------|-------|
|             | 0.111 | 0.177  | 0.015 | 0.697 |

Table 2. Here, $T_s$, $T_w$ and $T_{skid}$ are the temperatures of the gases, the furnace wall and the skids, respectively.

Meanwhile, the presence of the skid structure considerably distorts heat transfer to the slab surfaces, both as a result of radiative shielding of the slab bottom surface and conduction of energy across the slab/skid contact area. It is reported that conduction heat loss to the skid is found to be two orders of magnitude less than the reduction in radiative heat transfer to the slab and then the dominant factor in the formation of skid marks is the radiative shielding by skid structures. On the basis of the fact, it is assumed that conduction heat loss to the skid is negligible. Therefore, although the fixed skids are contact with the slab bottom surface in the real furnace, it is assumed that there is an interval of 0.005 m between the slab and fixed skid.

2.2. Governing Equations

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

$$\rho C \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) \quad \text{...........}(1)$$

where $\rho$, $C$, and $k$ represent density, specific heat, and conductivity of the slab, respectively. The boundary condition of the Eq. (1) is the total heat flux on the slab surface, $q_{slab}^R$, which can be obtained from the sum of the convective and radiative heat flux as following,

$$q_{slab}^R = q_{slab}^C + q_{slab}^R \quad \text{...........}(2)$$

where $q_{slab}^C$ and $q_{slab}^R$ are the convective and radiative heat flux, respectively. The convective heat transfer between the furnace gas and the solid surface is evaluated by using the equation,

$$q_{slab}^C = H_e (T_w - T_{slab}) \quad \text{...........}(3)$$

where $H_e$ is the gas convective heat transfer coefficient at the surface of the slab of 7.8 W m$^{-2}$ K$^{-1}$, when coke-oven gases are used as fuel. Also, $T_{slab}$ is the temperature of the slab surface.

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

$$q_{slab}^R = \int_{\Omega=4\pi} I(\vec{r}_w, \vec{s})(\hat{s} \cdot \hat{n}_w)d\Omega \quad \text{...........}(4)$$

where $I(\vec{r}_w, \vec{s})$ is the radiation intensity at the slab surface $\vec{r}_w$ and direction $\vec{s}$, $\hat{n}_w$ is the outward unit normal vector at the slab surface, and $\Omega$ is the solid angle. For a radiative active medium, the radiation intensity at any position $\vec{r}$ along a path $\vec{s}$ through an absorbing, emitting and scattering medium can be given by the following radiative transfer equation (RTE),

$$\frac{1}{\beta_0} \frac{dl(I(\vec{r}, \vec{s}))}{ds} = -I(\vec{r}, \vec{s}) + (1 - \omega_0) I_{b(\vec{r})} + \frac{\omega_0}{4\pi} \int_{\Omega=4\pi} I(\vec{r}, \vec{s}) \Phi(\vec{s} \rightarrow \vec{s})d\Omega' \quad \text{...........}(5)$$

where $\beta_0 = \kappa + \sigma_s$ is the extinction coefficient, $\kappa$ is absorption coefficient, $\sigma_s$ is scattering coefficient, $\omega_0 = \sigma_s/\beta_0$ is the scattering albedo, and $\Phi(\vec{s} \rightarrow \vec{s})$ is the scattering phase function of radiative transfer from the incoming direction $\vec{s}'$ to the scattering direction $\vec{s}$. $I_{b(\vec{r})}$ is the blackbody radiation of the medium. This equation, if the temperature of the medium, $I_{b(\vec{r})}$, and the boundary conditions for intensity are given, provides a distribution of the radiation intensity in the medium. For a diffusely emitting and reflecting wall with temperature $T_w$, the outgoing intensity at the wall which is the boundary condition of Eq. (5) can be expressed as the summation of the emitted and reflected ones like,

$$I(\vec{r}_w, \vec{s}) = \varepsilon_w I_{bw}(\vec{r}_w) + \frac{1 - \varepsilon_w}{\pi} \int_{\vec{n}_w < 0} I(\vec{r}_w, \vec{s}') |\vec{s}' \cdot \vec{n}_w| d\Omega' \quad \text{...........}(6)$$

where $\varepsilon_w$ is the wall emissivity, and $I_{bw} = \sigma T_w^4/\pi$ is the blackbody intensity of the wall.

2.3. Solution Method

The transient heat conduction equation expressed in Eq. (1) is discretized by using the finite volume method (FVM). A central differencing scheme is used for the diffusion terms in the $x$- and $y$-directions, while the unsteady term is treated implicitly. The resulting discretized system is then solved iteratively by using the TDMA (tridiagonal matrix algorithm) algorithm until the temperature field in the slab satisfies the following convergence criterion,

$$\max(|T_{ij}^n - T_{ij}^{n-1}|/T_{ij}^n) \leq 10^{-6} \quad \text{...........}(7)$$

where $T_{ij}^{n-1}$ is the previous value of $T_{ij}^n$ in the same time level.

Meanwhile, the RTE expressed in Eq. (5) must be analyzed in order to compute the radiative heat flux on the slab surface as shown in Eq. (4). In this work, the finite volume
method (FVM) for radiation suggested by Chui and Raithby,\textsuperscript{9) and developed by Chai et al.\textsuperscript{10) and Baek et al.\textsuperscript{10})} is adopted to discretize the RTE. More detailed information on the FVM can be easily found in the literature.\textsuperscript{5,8–10)}

3. Results and Discussion

The reheating furnace heat transfer model developed in this work was used to investigate several aspects of furnace behavior, especially focusing on the prediction of the effects of the skids and various parameters on the heating characteristics and thermal behavior of the slab.

As mentioned previously, in order to consider the nongray characteristics of the combustion gases, the WSGGM, which postulates that total emissivity and absorptivity may be represented by the sum of gray gas emissivities weighted with a temperature dependent factor, is used, and further information on the model is easily found in Smith et al.\textsuperscript{6) On the other hand, it is assumed that there is no scattering, i.e., $\sigma_t=0$. Because of its symmetry, a half of the furnace is modeled in order to reduce computing time. The spatial mesh systems used in this study is ($N_x \times N_y$)=(215$\times$101) and angular systems of ($N_{\phi} \times N_{\theta}$)=(4$\times$12) for $2\pi$ sr.

3.1. Effect of the Skid Structures

As shown in Fig. 1(b), fixed and moving skids are used in the walking-beam type reheating furnace, where the slabs are supported on the fixed skids. Therefore, the bottom of the slab is shielded and cooled by the skids, and temperature distribution within the slab adjacent to the contacting skids is expected to be depressed. Thus, a localized temperature depression known as skidmark can arise. Figure 2 shows the heat flux distribution on the slab surface and the temperature distribution inside the slab in each zone of the furnace according to existence and nonexistence of the skids. In this case, the slab residence time is 180 min, and emissivities of the furnace wall and the slab are 0.75 and 0.5, respectively. It can be seen from the figure that in both cases a large amount of heat energy is transferred to the slab in the non-firing zone and the charging zone because of the relatively high temperature difference between the slab and the surrounding combustion gases in these zones. This phenomenon is sustained up to the preheating zone, 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. On the other hand, slabs are further heated as they pass through the subsequent heating zone, and thereby, the peak temperature appears in this zone. In the final soaking zone, however, because not only the furnace temperature is slightly decreased by about 90°C than the previous heating zone but also the slab is at high temperature nearly the furnace gas temperature, it can be found that some heat flux is emitted from the hot slab to the surroundings. Therefore, temperature of the slab is slightly lowered and the temperature gradient within the slab becomes smaller.

Meanwhile, unlike the case in which the skids are not considered, the existing skids make the heat flux depressed around the slab and skid contact region due to the shielding effect of the skids as shown in Fig. 3, and thereby, the temperature of the slab in this region is relatively low as shown in Fig. 2. 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. 3. Finally, it can be seen from Fig. 4 that the centerline temperature of the slab, $T_{1,5C}$ at the furnace exit for the case considering the skids is lower by about 30°C than one of the case not considering the skids.
3.2. Comparison with the Experimental Data

The predicted temperature history in the slab using the present model is compared with the experimental data provided by POSCO, as shown in Fig. 5. In the figure, \( T_s,u \), \( T_s,c \), and \( T_s,b \) are mean temperatures on the top surface, centerline, and bottom surface of the slab, respectively. Note that although the uncertainty range of the measurements exists, there is a reasonable agreement between the predicted and measured temperature profiles. Especially, at the final soaking zone, the predicted temperature is in good agreement with the experimental data. This means that the present heat transfer model can be successfully applied to the walking beam type reheating furnace for the prediction of slab temperature.

3.3. Effect of the Residence Time

Furnace residence time is closely related to energy consumption and pollutant emissions. Thus, it is important to find the optimal residence time at given furnace conditions.

Figure 6 shows the effect of residence time on the longitudinal temperature profile of the centerline temperature of the slab. As shown, the temperature increases with residence time in the early zones of the furnace, but the final temperatures near the exit are relatively in the narrow limits, especially, nearly same since 180 min. Meanwhile, Table 4 lists the differences between maximum and minimum temperatures in the slab at the exit of the furnace. Thus, it is deemed the most efficient is to set the residence time to 180 min in this operating condition.

3.4. Effect of the Furnace Wall and Slab Emissivities

The emissivity of a material is the ratio of the energy radiated by the material to the energy radiated by a blackbody at the same temperature and a measure of a material’s ability to absorb and radiate energy. Figure 7 shows the effect of slab emissivity on the longitudinal temperature profile of the centerline temperature of the slab, where the emissivi-
ties of the furnace wall and skid structure are set to 0.75 and 0.5, respectively. As shown, the slab centerline temperature increases with slab emissivity because the slab can receive more heat impinging on the surface as the slab becomes black. However, it is noted that although the effect of slab emissivity is more evident within the furnace, the final temperature near the exit is relatively in the narrow limits.

Next, the effect of furnace wall emissivity on the temperature profile of the slab is shown in Fig. 8, where the emissivity of the slab is 0.5. As expected, the temperature increases with the furnace wall emissivity. The effect of the furnace wall emissivity, however, is smaller than that of the slab emissivity because heating of the slab mostly arises from the furnace gas rather than furnace wall.

3.5. Transient Variation of Various Heat Fluxes

Figure 9 represents the transient variation of various heat fluxes from hot gas and furnace wall to the slab surface, where emissivities of the furnace wall, slab and skid are kept at 0.75, 0.5 and 0.5, respectively. Further, furnace residence time is 180 min. The values in the figure are volume average values on the entire surface of the slab. It can be seen that over 90% of the heat flux comes from the radiation because the radiative heat flux is proportional to $T^4$, whereas the convective heat flux is proportional to $\Delta T$ in the furnace. This result is in line with the result from Han et al. Therefore, it is noted that the thermal radiation behavior in the reheating furnace should be predicted accurately for efficient and economic operation of the furnace as well as quality of the steel product.

4. Conclusions

In this work, a mathematical model of a walking-beam type reheating furnace has been developed and applied to investigate the heating characteristics of the slab. Based on the given longitudinal furnace gas and wall temperature, the model can predict the radiative and convective heat fluxes on the slab surface and the temperature distribution in the slab throughout the furnace. After discussing the thermal behavior in the reheating furnace with skids and validating numerical results by comparison with the experimental data conducted by POSCO, slab heating characteristics are investigated by changing such various parameters as residence time, emissivity of the slab, and emissivity of the furnace wall. It is found that the heat flux impinging on the slab surface is mainly originated from the thermal radiation in the furnace. Although the numerical results were for a specific example under consideration, the same methodology may be used to model any similar reheating furnace in the design phase or currently in operation.

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