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3-D Transient Heat Transfer Analysis of Slab Heating Characteristics in a Reheating Furnace in Hot Strip Mills

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***Abstract*—**The reheating furnace is used to reheat the steel slabs before the hot-rolling process. The supported system includes the stationary/moving beams, and the skid buttons which block some thermal radiation transmitted to the bottom of the slab**s**. Therefore, it is important to analyze the steel slab temperature distribution during the heating period. A three-dimensional mathematical transient heat transfer model for the prediction of temperature distribution within the slab has been developed. The effects of different skid button height (H=60mm, 90mm, and 120mm) and different gap distance between two slabs (S=50mm, 75mm, and 100mm) on the slab skid mark formation and temperature profiles are investigated. Comparison with the in-situ experimental data from Steel Company in Taiwan shows that the present heat transfer model works well for the prediction of thermal behavior of the slab in the reheating furnace. It is found that the skid mark severity decreases with an increase in the skid button height. The effect of gap distance is important only for the slab edge planes, while it is insignificant for the slab central planes.

***Keywords*—**3-D, slab, transient heat conduction, reheating furnace, thermal radiation.

I. Introduction

IN steel factories, the reheating furnace is used to reheat the steel slabs before the hot-rolling process. In the reheating process, the supported system includes the stationary beams, the moving beams, and the skid buttons which block some thermal radiation transmitted to the bottom of the slabs. Besides, heat may be conducted by the skid buttons from the steel slabs to the cooling water. Severely uneven temperature distribution of the steel slabs makes it difficult to produce superior steel product in the subsequent rolling process. In order to deal with the uneven temperature distributions at exit of the reheating furnace, therefore, it is important to develop an accurate numerical analysis model to analyze the steel slab temperature distribution during the heating period.

In recent years, the analysis of transient heating characteristics of the steel slabs in a reheating furnace has attracted considerable attention. Numerical heat transfer model has been developed by considering the thermal radiation in the furnace chamber and transient heat conduction in the slab [1]. Han et al. [2] studied the influence of the residence time of slabs inside a reheating furnace by calculating gas radiation with the finite volume method. They used the known temperatures of the wall and the medium for each sub-zones. Reducing residence time means the more efficiency of the productivity. However, too short of the residence time in reheating furnace cannot guarantee the quality of the product. Hsieh et al. [3] carried out an analysis that the skid mark is mainly caused by the radiation shielding effect of the walking-beam system and worsen by cooling system. To improve the skid mark, the static beams should be moved outward in the soaking zone and the height of the skid button should be increased. Han et al. [4] modelled the movement of slab by transferring the data of temperature from one slab to next one at different time with the user defined function implemented in commercial software FLUENT. The advantage is that the simulation can be done in a single integrated code of conduction and radiation. Han et al. [5] studied the thermal efficiency of 2-D reheating furnace for various fuel feeding rates for a reheating furnace with only axial-fired burners. The entire furnace was divided into fourteen sub-zones, and they set each sub-zones of the wall and the medium temperature which calculated by using overall thermal balance equation. Singh et al. [6] compared the four different heat transfer models for the prediction of temperature of the slabs in a walking beam type reheating furnace. The models are classified based on the solution methodology and simplifications. All the models have been compared for their performance and computational time.

In this study, the heating process during a five-zone reheating furnace operated by China Steel Corporation, in Taiwan is analyzed by a three-dimensional transient heat transfer model. The present model mainly analyzes the radiation heat transfer among the slabs, the skids, the beams, and the furnace walls as well as the conduction in the slab and skid. Skid beams are included to evaluate radiation shielding effects from furnace wall to the slab. The effects of different skid button height and different gap distance between two slabs on the slab skid mark formation and temperature profiles are investigated.

II. Furnace Description

The schematic diagram of the walking beam type reheating furnace is depicted in Fig. 1. This furnace has dimensions of 60 m in length, 10.5 m in width, and the highest furnace wall is about 5.2 m. It is composed of five zones, namely, non-firing, pre-heating, 1st-heating, 2nd-heating, and soaking zones; the length for each corresponding zone is 15.5 m, 11 m, 11.5 m, 11.5 m, 10.5 m, respectively. Slabs are elevated 2.485 m from the furnace ground. There are 44 slabs in the reheating furnace and the space between slabs is 0.08 m. All slabs have the same

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dimensions and properties. The slab has 9 m in length, 1.25 m in width, and 0.25 m in height. A fresh slab is fed into the reheating furnace from the left side of the furnace.

The mixing of the coke oven gas (COG) as the fuel are injected into the furnace with air through the nozzles at the top and bottom of the furnace. The hot gas flows along with the reverse direction of the slab to exit at the left side of the furnace.

The slabs are supported by the stationary beams, and heated on the stationary skid buttons. The slab is moved to the next stationary beam by the moving beam within every heating period.

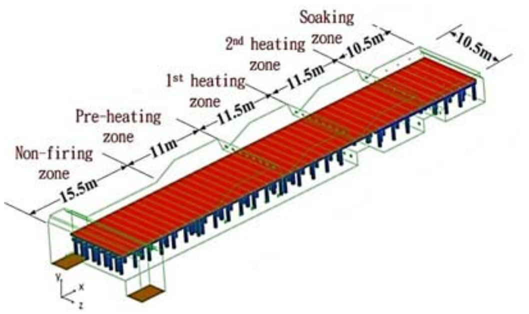


Fig. 1 Configuration of the reheating furnace

III. Theoretical Model

The physical model for the steady state walking beam type reheating furnace is simplified as a 3-D transient radiation and conduction problem, as shown in Figs. 2 (a) and (b). The simplified model is symmetric along the z=0 plane. Fig. 2 (a), which contains only one slab, is used to analyze the effects of different skid button height (H=60 mm, 90 mm, and 120 mm) on the slab skid mark formation; while Fig. 2 (b), which contains 3 slabs, is used to exam the effects of different gap distance between two slabs (S=50mm, 75mm, and 100mm) on the temperature profiles.

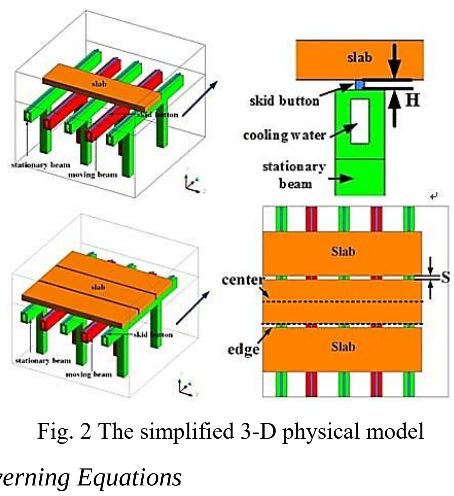


Fig. 2 The simplified 3-D physical model

A. Governing Equations

The three-dimensional transient heat conduction governing equation for the temperature field of the steel slab is as shown in (1):

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

where ρ, Cp, and k are density, specific heat, and thermal conductivity of the steel slab, respectively. The density is specified as a constant of 7871 kg/m^3; while the specific heat and the thermal conductivity of the slab are considered as functions of temperature.

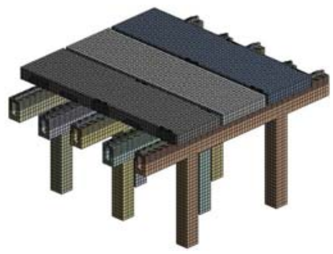


Fig. 3 Computational grid system

The effective radiation heat flux on the slab surface is composed of directly emitted and reflected energy. The reflected radiative heat flux is dependent on the incident from the surroundings which can be expressed in terms of the flux leaving all other surfaces. As shown in (2)

$$q_{out,i}=\varepsilon_i\sigma T_i^4+\rho_i\sum_{j=1}^{N}F_{ij}q_{out,j} \quad (2)$$

where q_{out} is the radiative heat flux leaving the surface, ε is the emissivity, σ is Boltzmann's constant (σ = 5.67 × 10^{-8} W/m^2·K^4).

The View factor F_{ij} between two finite surface i and j is given by (3):

$$F_{ij}=\frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{\cos\theta_i\cos\theta_j}{\pi r^2}\delta_{ij}dA_idA_j \quad (3)$$

where δ_{ij} is determined by the visibility of dA_j to dA_i. $\delta_{ij}=1$ if dA_j is visible to dA_i and equals to 0 otherwise.

B. Boundary Conditions

The initial temperature of the slab, supported beams, and skid buttons at the entrance of the furnace is assumed to be uniform temperature at 300K. The slabs reside in the reheating furnace for 200 minutes. The wall temperature is a function of time shown in Fig. 4. The emissivity of the furnace wall is 0.9 while that of the beam is 0.6 and the skid button is 0.4. The density, thermal conductivity, and specific heat for the beam/ skid button are 3300/8100 kg/m^3, 3.2/35 W/m·K, and 1170/980 J/kg·K., respectively. The temperature for the cooling water is assumed as T_∞ =308 K and the convection heat transfer coefficient h=1800 W/m^2·K.

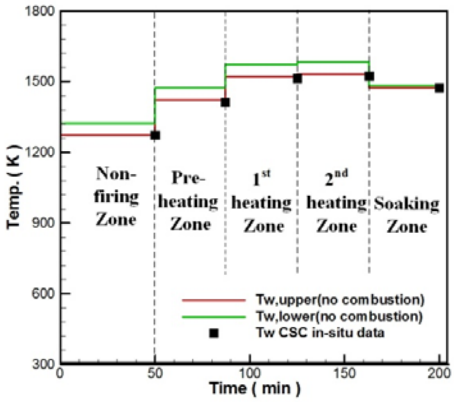


Fig. 4 The boundary condition for the furnace wall temperature history vs. time

IV. Numerical Analysis

The governing equations and boundary conditions are solved using commercial software FLUENT. In this study, the governing equations are solved numerically using a control volume base on the finite difference method. The finite difference method incorporating a second order central difference and fully implicit schemes was adopted to simulate the heat transfer phenomenon of the slab with the time step of 30 seconds. Fig. 3 shows the computational grid which is composed of 1,544,164cells. The resulting discretized system is then solved iteratively until the temperature field satisfies the following convergence criterion:

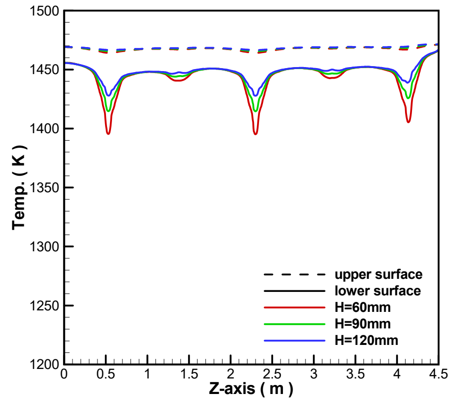
$$\max\left(\frac{\left|T_{i,j,k}^{n}-T_{i,j,k}^{n-1}\right|}{T_{i,j,k}^{n}}\right)\leq 10^{-7} \quad (4)$$

where $T_{i,j,k}^{n-1}$ is the previous value of $T_{i,j,k}^{n}$ at the same time level.

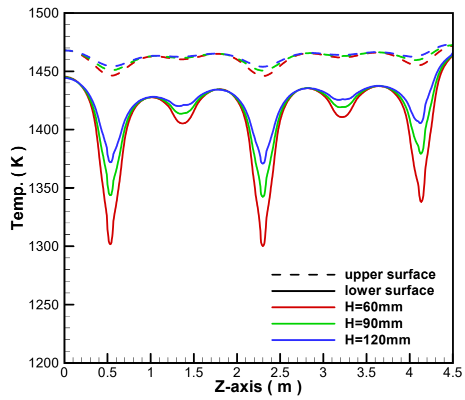
V. Results and Discussion

Figs. 5 (a) and (b) illustrate the slab temperature distribution at the edge plane and the central plane, respectively, at the exit of the reheating furnace for three different skid button height (H=60 mm, 90 mm, and 120 mm). The dashed lines represent the upper surface temperatures, while the solid line denotes the lower surface temperatures. It is seen that the walking-beam system which blocks some thermal radiation transmitted to the bottom of steel slabs causes uneven temperature distributions across upper surface and lower surface of the slab. From Fig. 5 (a), at the edge plane, one can observe that, as the skid button height is increased from 60 mm to 120 mm, the skid mark severity, defined as the average temperature difference between the upper and lower surfaces, is decreased from 24 K down to 20K. For Fig. 5 (b), at the central plane, as the skid button height is increased from 60 mm to 120 mm, the skid mark severity is decreased from 49 K down to 39K. This is due to that fact that, the presence of the pillars at the center of the steel slab, it blocks more thermal radiation transmitted to the bottom of the slabs.

Fig. 6 shows the slab heating curves for the upper and lower surfaces for different H. The predicted temperature history in the slab is also compared with the data of in-situ measurement conducted by China Steel Corporation in Taiwan. It is seen that there exists a reasonable agreement between the predicted and measured temperature distribution.



(a) edge



(b) center

Fig. 5 Temperature profile of the slab at exit (t=200 min) for different H

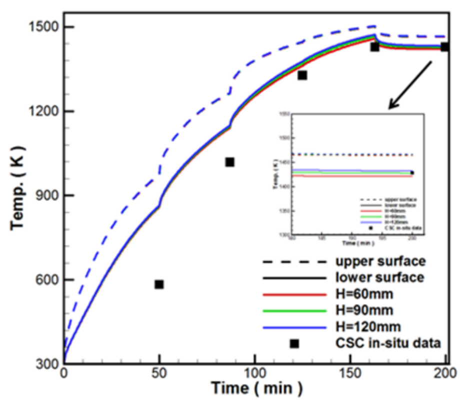
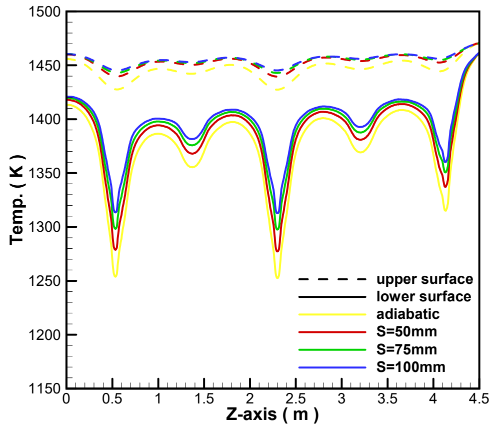
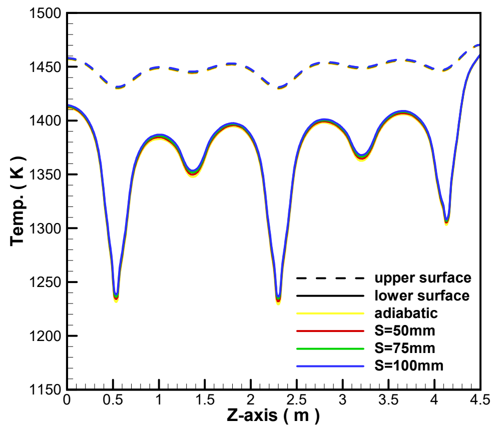


Fig. 6 The slab heating curves for the upper and lower surfaces for different H

Figs. 7 (a) and (b) show the slab temperature distribution at the edge and central plane, respectively, at the exit of the reheating furnace for three different gap distance (S=50mm, 75mm, and 100mm). The dashed lines represent the upper surface temperatures, while the solid line denotes the lower surface temperatures. When the gap distance S is increased, less thermal radiation transmitted to the edge plane of the slab is blocked from the adjacent slabs. At the edge plane, one can observe that, as S is increased from 50 mm to 100 mm, the skid mark severity is decreased from 67 K down to 58K. While for the central plane, as S is increased from 50 mm to 100 mm, the skid mark severity is decreased from 77 K down to 76K. It is also observed that the effect of gap distance between two slabs is important only for the edge plane, while it is insignificant for the slab central plane.



(a) edge



(b) center

Fig. 7 Temperature profile of the slab at exit of furnace (t=200 min) for different S

Fig. 8 shows the slab heating curves for the edge and the central plane for different S. There is a significant difference in heating curve between the edge and the central planes during the early heating period. The largest difference is in the 2nd-heating zone. When slab reaches the exit of the reheating furnace, the temperature difference becomes smaller. This can be explained that the temperature within the slab tends to be uniform in the soaking zone.

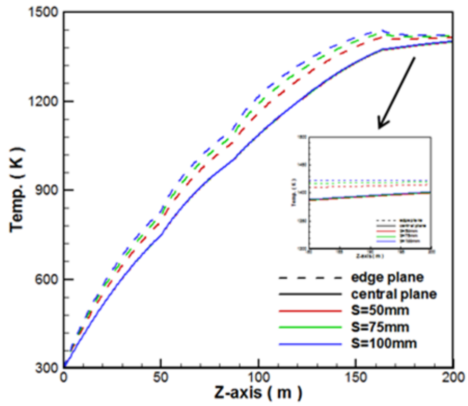


Fig. 8 The slab heating curves for the edge and the central planes for different S

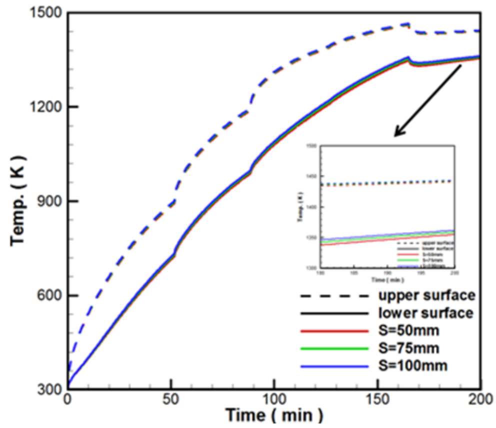


Fig. 9 The slab heating curves for the upper and lower surfaces for different S

Fig. 9 shows the slab heating curves for the upper and lower surfaces for 3 different gap distance between slabs (S= 50 mm, 75 mm, and 100mm). It reveals that the effect of different gap distance has little influence for both upper and lower surface temperature history vs. time.

III. Conclusion

A three-dimensional mathematical transient heat transfer model has been developed to predict the temperature uniformity within the slab. The present model mainly analyzes the radiation heat transfer among the slabs, the skids, the beams, and the furnace walls as well as the conduction in the slab and skid. The effects of different skid button height and different gap distance between two slabs on the slab skid mark formation and temperature profiles are investigated. The following conclusions are yielded based on the obtained results:

1) It is shown that the skid mark severity decreases with an increase in the skid button height.
2) For the edge plane, as the skid button height is increased from 60 mm to 120 mm, the skid mark severity can be reduced from 24 K down to 20K; while for the central

plane, it can be decreased from 49 K down to 39K.

3) The effect of gap distance between two slabs is important only for the edge planes, while it is insignificant for the central planes.
4) For the edge plane, as the gap between slabs is increased from 50mm to 100mm, the skid mark severity can be reduced from 67K down to 58K; while for the center plane, it can be decreased from 77K down to 76K.

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