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Analysis of slab heating characteristics in a reheating furnace

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ABSTRACT

For a reheating furnace, an analysis of thermal efficiency depends on precise investigations of the combustion and flow characteristics inside a furnace. Especially, the flow field of the hot gas has significant influence on heating slabs. The slabs are heated up to the temperature over 1500 K, and then they are transported to the rolling mill. The heating efficiency is affected by many factors, such as fuel type, locations of both slabs and burners, thermal properties of slabs, geometry of slab supporting systems, and so on. In the paper, some efforts were made to simulate the thermo-fluid mechanical phenomenon inside the furnace. The slab heating characteristics in the reheating furnace were investigated by using the finite-volume method (FVM). The unsteady calculation was performed to obtain the temperature distribution by considering the movement of the slabs in the reheating furnace. To treat radiation emitted by the walls and the gas, numerical simulations were completed by employing ANSYS FLUENT. The configurations of skid posts and beams were also considered to evaluate the effect of the burner position. Results indicate that the case with 6 side burners has a higher heating efficiency both in the heating and soaking sections.

1. Introduction

Industrial furnaces are important heating equipment. The consumption from industrial furnaces is the second largest energy consumption in China, right after the thermal power generation. The average thermal efficiency of industrial furnaces in China is about 30%, and it is lower than that in other developed countries which is about 50%. It is necessary to improve the product quality and reduce the energy consumption according to the energy shortage and the competition from the steel industry. To reduce the carbon emissions of the local energy sector, Perry et al. [1] proposed that total site targeting should be applied to locally integrated energy sectors. Baleta et al. [2] presented mathematical models for description of selective non-catalytic reduction process, and they validated and parameterized the urea decomposition model. Flamme [3] investigated low NO_x combustion technologies for high temperature applications, and he found that the NO_x emissions are very high by using conventional burners. Hou and Ko [4] examined effects of the heating height on flame appearance, temperature field and efficiency of an impinging laminar jet flame in domestic gas burners. They found that the maximum thermal efficiency occurs if the inner rich premixed flame is higher than the heating height. Chandok et al. [5] estimated the furnace exit gas temperature (FEGT) by using optimized radial basis and neural networks. Results showed that the radial basis function networks are about 10 times faster than multilayer perceptron networks with a back-propagation algorithm. To improve the thermal efficiency, Wang et al. [6–8] investigated effects of the deposition configurations on the cooling effectiveness in the heat transfer process. Other spectral method is also applied to heat transfer field [9–12].

In order to maintain a high thermal efficiency, many scholars have studied the combustion in a heating furnace. Liu et al. [13] conducted numerical simulations on slab heating characteristics in a reheating furnace, and a basic model was proposed to improve the heating efficiency. Considering various fuel feed conditions, Han et al. [14] calculated radiative heat transfer using a finite volume method (FVM) and a blocked-off procedure was adopted for the treatment of the slabs. Prieler et al. [15] predicted the gas phase combustion, heat transfer and transient heating characteristics of the billets in a furnace by computational fluid dynamics (CFD), and they found that 93% of the total heat flux to the billet

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Nomenclature

$C_{p,k}$	specific heat of k-th species, J/(kg K)
D_1	outer diameter of the burner, mm
D_2	inner diameter of the burner, mm
f	mixture fraction
f'	mixture fraction variance
k	turbulent kinetic energy, m^2/s^2
P	pressure, N/m^2
S	source term
T	temperature, K
t	time, s
u	velocity, m/s
x, y, z	coordinates, m
Y_k	mass fraction of k-th species

Greek symbols

ε	turbulence dissipation rate, m^2/s^3
μ_t	turbulent viscosity, kg/s m
ρ	density, kg/m^3
ϕ	arbitrary variable
Ω	solid angle

Subscripts

i, j, k	indices

Superscripts

–	time-average term
~	favre-average term

comes from radiation. Emadi et al. [16] developed a mathematical heat transfer model to investigate the heating characteristics of billets in a reheating furnace. They found that 5% reduction of the residence time can be obtained by increasing the surface emissivity from 0.7 to 0.95. Han and Chang [17] calculated radiation heat transfer by the FVM solving method. Results showed that most of the blast furnace gas (BFG) and the coke oven gas (COG) do not satisfy the slab emission requirement. Considering the effect of the furnace wall, Kim [18] calculated the radiative heat flux in a furnace by the FVM, and the model predicted the temperature distribution of the slab. Jang et al. [19] developed a mathematical model for a reheating furnace, and results indicated that the effect of the scale layer on the slab heating is significant. Han et al. [20–23] investigated slab heating characteristics in similar reheating furnaces installed in Pohang Iron and Steel Company (POSCO) by using the commercial code ANSYS FLUENT. They processed quick movements of the slabs using a developed user defined function (UDF). Results showed that the corner of the slab is heated faster than any other region because of different thermal resistances. They also found that a slab is mostly heated in the preheating and heating sections, and the temperature of the slab is raised very little in the soaking section. However, there are main differences in geometry structures between the computational domains to obtain the conclusions above. The configuration in Ref. [20] is too simple to represent the real structure compared to Refs. [21–23], while a skid system is not included in Ref. [23] compared to Refs. [21,22]. Two walking beams are assumed to remain at the same elevation as the static beams in Ref. [21], while the two walking beams stay in lower elevation than three static beams in Ref. [22]. Gu et al. [24] numerically analysed the slab heating process in a walking beam regenerative furnace, considering both the reverse combustion and the slab movement. They found that the surface temperature rises faster than the center point temperature in the preheating and heating sections.

To analyze the temperature distributions, effects of the burner position and the number of burners were not considered in Refs. [17–23], although the researchers investigated effects of gas compositions, heat transfer model, skid system, formation and growth of the scale layer on the slab, etc. The present research aims to report transient heating characteristics of slabs inside a furnace by considering a similar arrangement of skid beams in Ref. [22]. The effect of the burner arrangement on the temperature distribution is investigated by using a three-dimensional geometrical model from the POSCO Company. In this study, unsteady calculations considering the movement of slabs are performed to get periodically transient solutions by using the commercial software ANSYS FLUENT 16.0.

2. Numerical model and validation

To investigate the effect of the burner arrangement on the temperature distribution, a 3D (three-dimensional) geometrical model is shown in Fig. 1. There are three cases used for numerical simulations as listed in Table 1. The furnace geometry operated in the POSCO Company is used in present research. The full size of the furnace with 29 slabs has the dimensions of 34.8 m × 5.02 m × 10.8 m. It is divided into three parts, i.e., preheating section, heating section and soaking section.

There is a symmetry wall at z = 0, and the geometry just shows half the furnace. For a geometrical model, 5 skid beams are used to support the slabs. Three static beams are given a higher height than the other two walking beams as shown in Fig. 1. The dimensions of each half slab are 1.02 m × 0.23 m × 4.8 m. The distance between adjacent slabs is 0.16 m, and more details are shown in Fig. 2.

The half furnace is equipped with 13 side burners in the lower zone and 12 axial burners in the upper zone. Two circles are used to simplify every burner. The fuel passage is simplified by the inner circle, and the annulus area between the two circles is used for the oxidizer passage. Additional dimensions for the geometrical model can be also found in Refs. [20–23].

2.1. Governing equations

The standard k-ε turbulence model is adopted in the present study. Considering that the slabs are transported out of the furnace at every time interval, the slab moving and the temperature distribution in the furnace are periodically transient. Favre averaging is used in compressible flow to separate turbulent fluctuations from the mean-flow. The instantaneous Favre-averaged equations of continuity, momentum, energy, turbulent kinetic energy, eddy dissipation rate can be written as follows

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial (\bar{\rho}\tilde{u}_j)}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial (\bar{\rho}\tilde{u}_i)}{\partial t} + \frac{\partial (\bar{\rho}\tilde{u}_j\tilde{u}_i)}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right) - \left(\frac{2}{3}\mu\delta_{ij}\frac{\partial \tilde{u}_k}{\partial x_k}\right)\right] - \frac{\partial \tilde{p}}{\partial x_i} - \frac{\partial\left(\overline{\rho u_i'' u_j''}\right)}{\partial x_j} \tag{2}$$

$$\frac{\partial (\bar{\rho}\tilde{h})}{\partial t} + \frac{\partial (\bar{\rho}\tilde{u}_j\tilde{h})}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_t}{\sigma_h}\frac{\partial \tilde{h}}{\partial x_j}\right) + \tilde{S}_h \tag{3}$$

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