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Modeling of the slab heating process in a walking beam reheating furnace for process optimization

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ABSTRACT

A new methodology involving the integration of a three-dimensional (3D) Computational Fluid Dynamics (CFD) model and a two-dimensional (2D) heat transfer model for the study of the slab reheating process in a walking beam reheating furnace has been proposed. A comprehensive 3D CFD model has been developed to simulate the flow characteristics, combustion process and multi-mode heat transfer phenomena inside an industrial slab reheating furnace. A customized 2D heat transfer model for the slab reheating process has also been developed based on the finite difference method. The simulation results from the 3D CFD model provide detailed heat transfer boundary conditions for the 2D heat transfer model. Instrumented slab trials were conducted under typical operating conditions of the furnace and the results were used to calibrate the 2D model. By comparing the slab temperatures measured from the instrumented slab trials and those predicted using the models, it was demonstrated that the 3D CFD and 2D heat transfer models predict the reheating process reasonably well. The proposed methodology is fairly easy to be used by mill engineers for trouble shooting and optimizing of the slab reheating process.

1. Introduction

The slab reheating furnace is widely used by steel mills to elevate steel slab temperature for further processing. Before a slab is rolled to a final product thickness, it is heated up in a furnace to approximately 1500 K with a temperature gradient inside the slab below 50 K/m [1,2]. Achieving a targeted bulk slab temperature with good uniformity along the slab length and through the slab thickness is a basic requirement for reheating furnace control. Very often, slab reheating is a bottleneck to the productivity of most of steel mills due to the difficulty of achieving a good balance between reheating quality and furnace throughput.

The slab reheating furnace operation is a complex physical and chemical process which involves combustion, heat exchange among furnace wall, flame, skid and steel slabs, slab movement, and slab internal heat conduction [3]. A well operated reheating furnace should have characteristics such as high thermal efficiency, low emission, and well controlled slab discharging temperature [4,5]. The first step towards achieving better control of the reheating furnace operation is to fully understand the physical and chemical processes inside the reheating furnace. Physical experimentation such as instrumented slab trials is a practical way which is used by steel mills to obtain a better understanding of reheating furnace operations. However, the cost of a full-scale instrumented slab trial is very high [6]; therefore, numerical methods such as CFD can be used to conduct computational experiments which are not only cost-effective but reliable.

A number of studies have been conducted regarding the use of CFD for analyzing reheating furnace operations. The scopes of modeling reheating furnaces can be divided into the following categories: furnace combustion modeling, heat transfer modeling including the slab heating process and the skid mark effect, slab residence time optimization, thermal efficiency analysis, environmental effect investigations [7,8], and slab surface scale effects [9,10]. Numerical investigation on the reheating furnace flow and combustion is the basis for further study of the slab reheating characteristics. Hsieh and Kim et al. [11,12] investigated reheating furnace combustion without considering the transient slab heating process. They applied the probability density function (PDF) turbulence combustion model to the simulation of the combustion process. The discrete ordinate radiation model and weighted-sum-of-gray-gases model (WSGGM) were used to describe the radiation within the reheating furnace. Kim et al. [13,14] investigated the effect of heat transfer models on the prediction

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Nomenclature

p	static pressure, pascal
ρ	density, kg/m^3
$\bar{F}$	external body force, N
$\bar{g}$	gravity, m/s^2
$\bar{\bar{\tau}}$	stress tensor
μ	molecular viscosity, kg·m/s
I	unit tensor
k_{eff}	effective conductivity, W/m K
h_j	sensible enthalpy of species j
$\vec{J}_j$	diffusion flux of species j
S_h	heat of chemical reaction, and any other volumetric heat sources, J
k	turbulence energy, m^2/s^2
$\vec{v}$	velocity, m/s
u_j	velocity component along the direction x_j, m/s
u'_i	instant turbulence velocity on the direction x_i, m/s
a	absorption coefficient, m^{-1}
n	refractive index
σ_s	scattering coefficient, m^{-1}
σ	Stefan-Boltzmann constant (5.669×10^{-8} W/m$^2 - K^4$)
T	local temperature, K
Y_i	local mass fraction of each species
R_i	net rate of production of species i by chemical reactions
$\vec{j}_i$	diffusion flux term of species i
$D_{i,m}$	diffusion coefficient for specie i in the mixture
$D_{T,i}$	thermal diffusion coefficient
μ_t	turbulent viscosity
Pr_t	turbulent Prandtl number, 0.85
Sc_t	turbulent Schmidt number, 0.7
Y_i^*	mass fraction of species i within the fine structures after reacting over the time τ^*
Y_i^0	mass fraction of species i in the fluid surrounding the fine structures
ξ^*	mass fraction occupied by the fine structure regions
C_ξ	volume fraction constant, 2.1377
v	kinematic viscosity, m^2/s
$T(x,y,t)$	temperature at time step t
x	slab longitudinal direction coordinate
y	gauge direction coordinate
$C_s(t)$	specific heat of the slab
ρ_s	density of the slab
$K_s(t)$	thermal conductivity of the slab
Δx	increment of x coordinate
Δy	increment of y coordinate
Δt	increment of time
$T_{i,j}^t$	node temperature at time step t,
$T_{i,j}^{t+\Delta t}$	node temperature at time step $t + \Delta t$
G	gauge of the slab
$T(x,G,t)$	top surface (y = G) temperature at time step t
f	view factor
σ	Stefan-Boltzmann constant
ε_s	emissivity of the slab
T_{itop}	top chamber furnace temperature
h_i	the convective heat transfer coefficients

of steel slab temperature. Their research shows that heat transfer within a reheating furnace includes all modes, but the radiative heat transfer is dominant, occupying over 90% of the total heat transfer. By applying the discrete ordinate heat transfer model and the finite volume solution method, Kim was able to develop a heat transfer model which worked well for predicting the slab temperature in the reheating furnace. Singh claimed that the skid supporting system has little effect on the temperature distribution of a slab. However, the effect of the water cooled skid on the slab temperature distribution could be large according to the research of Jang et al. [15–18]. Kim et al. [16] studied the effects of different shapes of skid buttons on the slab temperature distribution. The results indicate that it is better to increase the exposure area of the skid button, which will increase the total heat transfer to the coolant and decrease the heat conduction between the parts, thereby reducing the severity of the skid marks on the slab. Jang et al. [19] developed an algorithm with a simplified conjugated-gradient method and a shooting method to optimize the heating pattern, thereby minimizing energy consumption. Their results indicate that the decrease of the preheating zone temperature will lead to a significant decrease in energy consumption.

The slab reheating furnace is large and requires a large number of grids in the CFD model to capture the details of fluid flow, combustion, and heat transfer characteristics. Therefore, the models developed recently by some researchers employed some simplifications, such as dividing the reheating furnace into several zones and assuming constant temperature in each zone [15,20,21]. Some also simplified the complex movement process [3,22,23]. However, these simplifications often introduce significant errors in the modeling. For example, in a real reheating furnace operating process, dynamic phenomena such as variation in slab walking speed, variation in fuel input, and different steel grades being heated. All of these can affect the furnace conditions such as velocity field, combustion process, and heat transfer characteristics. There are few studies dealing with a full-scale simulation of an industrial reheating furnace operation with these detailed dynamic phenomena.

Other researchers developed simplified models, such as heat transfer models focusing on a single slab to achieve high calculation efficiency. Chen et al. [24] developed a slab temperature model based on the finite difference method. By optimizing the reheating process, the total furnace residence time for a slab was reduced by 13 min in average, which corresponds to an increase in furnace throughput of 9.72%. However, the model used a zone method with a limited number of zones (6) in the furnace, which may have resulted in inaccurate thermal boundary conditions. Jang et al. [17] developed a billet heat transfer model based on a 2D Finite Element Method (FEM) model to obtain the temperature distribution of a billet during the reheating process. In this model, an optimization algorithm was proposed to minimize the difference between the model outputs and the measurements. However, the model focused on radiative heat transfer and took into account the convective heat transfer by adjusting the emission factor. Jaklic et al. [25] developed an online simulation model for the slab reheating process in a pusher-type furnace. The model considered the exact geometry of the furnace and slabs and was validated by comparing the measured and calculated slab heating curves. However, the model simplified the furnace temperature field using a zone method and applied a constant convective heat transfer coefficient. These simplifications may have hampered the model's ability to recreate the furnace condition, and therefore affected the accuracy of the model predictions.

In this paper, a comprehensive transient CFD model was developed by taking into account the flow characteristics, combustion, all modes of heat transfer, and dynamic interactions. The CFD model provides the basic understanding of the combustion, furnace atmosphere, and slab reheating process. In addition, it can