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Investigation of the slab heating characteristics in a reheating furnace with the formation and growth of scale on the slab surface

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ABSTRACT

In this work, the development of a mathematical heat transfer model for a walking-beam type reheating furnace is described and preliminary model predictions are presented. 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, including the radiant heat transfer among the slabs, the skids, the hot combustion gases and the furnace wall as well as the gas convection heat transfer in the furnace. In addition, present model is designed to be able to predict the formation and growth of the scale layer on the slab in order to investigate its effect on the slab heating. A comparison is made between the predictions of the present model and the data from an in situ measurement in the furnace, and a reasonable agreement is found. The results of the present simulation show that the effect of the scale layer on the slab heating is considerable.

1. Introduction

The reheating furnace process, that is the midway step between the continuous casting process and the hot-rolling process, is commonly used to raise the temperature of the slab, and, thereby, the plasticity of the slabs so that the subsequent hot-rolling process runs on wheels. Since the reheating furnace process should have lower energy consumption and combustion-generated 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 reheating 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.

These analytical studies can be classified into following two categories. The first one [1–5] is to solve the full Navier–Stokes and energy conservation equations governing the hot gas flow and combustion process in the furnace, where the thermal radiation acts as an energy source term via the divergence of radiative heat flux. 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 [6–12], 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. The model suggested in this work can be also categorized as the second approach.

Meanwhile, the reheating furnace is filled with hot-oxidizing combustion gases that mainly consist of H_2O, CO_2, O_2, and N_2. The steel slabs are heated up by these gases. As the steel surface temperature rises, however, it reacts with the furnace gases resulting in the formation of iron oxide layer that is generally termed scale. The thickness of the scale layer depends on slab residence time in the furnace, its surface temperature, temperature and aggressiveness of the furnace gas. The formation of scale causes physical loss of the slab. In addition, since the thermal conductivity of scale is very small compared to that of steel, the existence of scale on the slab can greatly affect the heat transfer behavior. However, the previous works to predict thermal heating characteristics of the slab in a reheating furnace have not ever considered the existence of scale.

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Nomenclature

C	specific heat, J/(kg K)
I	radiation intensity, W/m^2
N_ϕ, N_θ	discretized number of each radiation direction
$\vec{n}$	unit normal vector on control surface
q^C_{slab}	convective heat flux, W/m^2
q^R_{slab}	radiative heat flux, W/m^2
q^T_{slab}	total heat flux, W/m^2
$\bar{r}$	position vector
$\vec{s}$	unit direction vector
T	Temperature, K
k_p	parabolic rate constant
R	universal gas constant, J/(mol K)
Q	activation energy, J/mol

Greek symbols

ρ	density of slab or scale, kg/m^3
β_0	extinction coefficient, $=\kappa_a+\sigma_s$, m^{-1}
κ_a	absorption coefficient, m^{-1}
σ_s	scattering coefficient, m^{-1}
σ	Stefan–Boltzmann constant, =5.67 × 10^{-8} W/(m^2 K^4)
Φ	scattering phase function, sr^{-1}
Ω	solid angle, sr

Thus, the current work would suggest a mathematical heat transfer model to predict the formation and growth of the scale, and find the heat flux impinging on the slab surface and temperature distribution inside the slab considering it. 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 weighted sum of gray gas model (WSGGM) [13] is used to consider the non-gray 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 formation and growth of scale and its effect on the heat transfer characteristics and thermal behavior of the slab are investigated. Finally, some concluding remarks are given.

2. Theoretical models

2.1. Reheating furnace process and furnace model

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

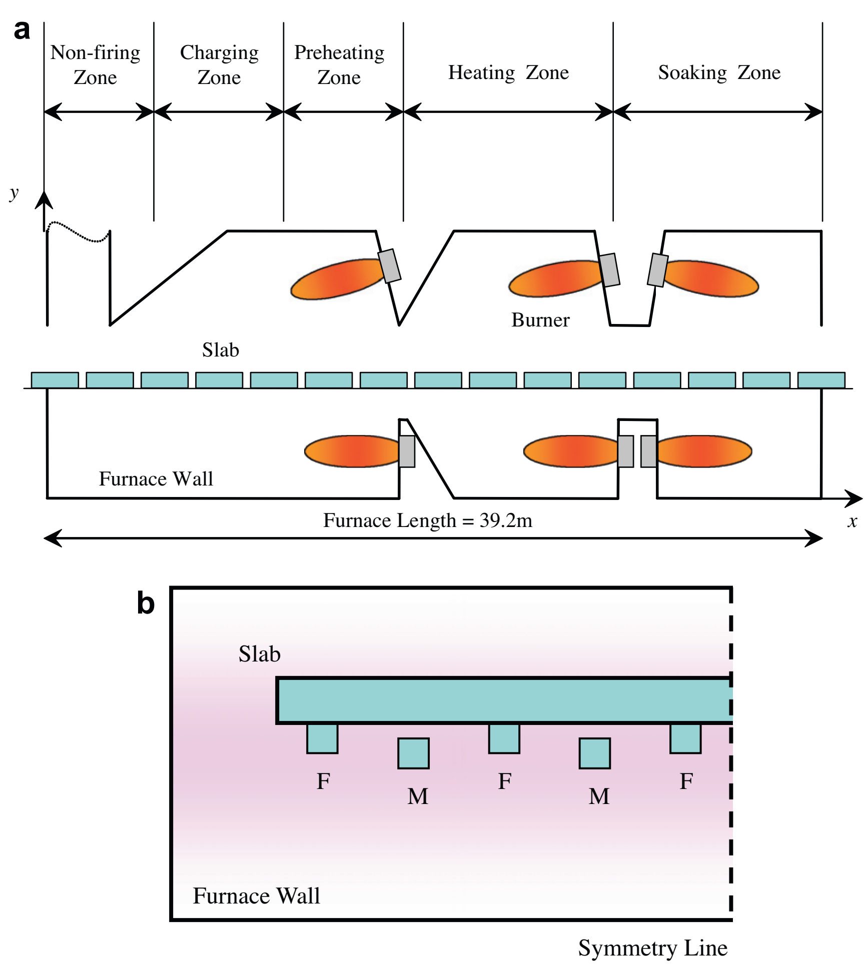

Fig. 1. Geometry of the reheating furnace: (a) longitudinal and (b) transverse sections.