International Journal of Thermal Sciences 84 (2014) 214–227

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Development of three dimensional transient numerical heat conduction model with growth of oxide scale for steel billet reheat simulation

Satish Kumar Dubey*, P. Srinivasan

Mechanical Engineering Department, Birla Institute of Technology & Science, Pilani, Rajasthan 333031, India

ARTICLE INFO

Article history:
Received 19 October 2013
Received in revised form
8 April 2014
Accepted 22 May 2014
Available online

Keywords:
Transient
Heat conduction
Reheat
Oxide
Finite difference
Implicit
Simulation

ABSTRACT

This paper presents development of numerical heat conduction model for prediction of transient three dimensional temperature field in the billet. The model is applied to billet heating process in the reheat furnace. The discretization of governing equation is done by control volume approach and implicit scheme of finite difference method. The model captures various time dependent boundary conditions corresponding to the billet reheat in the reheat furnace, in addition to this it also accounts for the growth of oxide scale layer on the billet surfaces during reheat simulations. The set of discretized equations is solved using own developed MATLAB® code. The proposed model is capable of predicting the temperature field in the billet and scale growth on the billet surfaces. The model is validated with analytical results and published experimental results. The results obtained through the model simulations are in concurrence with the anticipated trend. The proposed methodology of numerical modeling will be helpful for the temperature and scale growth predictions, which are vital for a variety of reasons like energy efficiency, process optimization, roll force calculations, carbon segregation control and product microstructure control, etc.

1. Introduction

The reheat furnaces are used in the steel industries for heating of steel billets before rolling processes. The reheat furnaces used in steel industries are either pusher type or walking beam type. It is the key prerequisite in both types of furnaces that the temperature of billets should be close to a target temperature. The furnace operations need to be designed and performed in such a way that the temperature gradient within billet does not exceed certain limit. During reheating at high temperature, steel billet surfaces react with furnace gases which is termed as oxidation reaction. As a result of this oxidation reaction, a layer of iron oxide starts growing on the billet surfaces. The formation and growth of oxide scale affect the heat transfer characteristics to a great extent due to the poor thermal conductivity, less emissivity and large specific heat of oxide scale in comparison to steel billet. The oxidation reaction is exothermic in nature, which may also affect the heat transfer characteristics.

Knowledge of transient temperature field in the billets at various stages like during reheat and at the end of reheat, are vital for numerous reasons like energy efficiency, process optimization, roll force calculation, carbon segregation control and microstructure control, etc. However, it is almost formidable to obtain correct and complete transient temperature field of the billet through measuring equipments. Developing an analytical solution to the problem is very difficult due to the complexities associated with the changing boundary conditions and large number of parameters affecting the process. A suitable numerical model may offer a valuable tool for the temperature field predictions.

Need for energy efficiency, sustainable development and quality have attracted a great deal of attention towards the numerical modeling of processes in steel industries. In the recent past, there have been continuous efforts to model reheat furnace operation. Numerical modeling of the billet reheating furnace was performed by Li et al. [1]. They calculated two dimensional temperature field in the billet during reheat. Mogan [2] performed two dimensional heat conduction modeling with oxide scale. Barr [3] performed thermal modeling for the pusher reheat furnace using the zone method and finite difference method. The model was used to predict two dimensional temperature field in the billet and to study the influence of skid designs on skid mark severity. Lindholm and Leden [4] presented finite element model to predict three dimensional temperature field in the billet during reheat. Finite volume based radiation heat transfer analysis for pusher type reheat furnace was

* Corresponding author. Tel.: +91 1596 515861; fax: +91 1596 244183.
E-mail address: sdubeybits@gmail.com (S.K. Dubey).

http://dx.doi.org/10.1016/j.ijthermalsci.2014.05.022
1290-0729/

Nomenclature

Abbreviations

FDM	finite difference method
FVM	finite volume method

Dimensionless number

Bi	Biot number
Fo	Fourier number

Indices

i	index in x
j	index in y
k	index in z
Δx	grid space in x direction
Δy	grid space in y direction
Δz	grid space in z direction
Δt	time step

Symbols

A_n	coefficient in series solution
A	Arrhenius constant
A_{gs}	gas absorptivity for radiation from the billet
A_{gm}	mean gas absorptivity for radiation from billet and wall
A_{gw}	gas absorptivity for radiation from the walls
ΔA	correction factor for absorptivity
b_n	Eigenvalues
c	specific heat capacity (J/kg K)
c_{os}	specific heat capacity of oxide scale (J/kg K)
c_{st}	specific heat capacity of steel (J/kg K)
d	skid button height (m)
F	shielding factor
h	heat transfer coefficient (W/m^2 K)
h_c	convection heat transfer coefficient (W/m^2 K)
h_{rg}	radiation heat transfer coefficient for billet and furnace gas (W/m^2 K)
h_{rw}	radiation heat transfer coefficient for billet and furnace wall (W/m^2 K)
h_w	convective heat transfer coefficient in skid pipe (W/m^2 K)
H	heat of oxidation reaction (J/kg)
k	thermal conductivity (W/m K)
k_{os}	thermal conductivity of oxide scale (W/m K)
k_{st}	thermal conductivity of steel (W/m K)
k_{sk}	thermal conductivity of skid button (W/m K)
h_{ct}	contact coefficient between skid and billet (W/m^2 K)
L_{bm}	furnace gas layer thickness (m)
m	mass (kg)
R	gas constant (J/mol K)
R_{bt}	overall thermal resistance for skid contact
T	temperature (K)
T_g	furnace gas temperature (K)
T_w	furnace wall temperature (K)
T_s	billet surface temperature
T_{water}	water temperature flowing through skid
Q	activation energy (J/mol)
$\dot{q}$	heat generated (W/m^3)
q	heat flux (W/m^2)
q_t	total heat flux (W/m^2)
$q_{\text{bottom},1}$	total flux for bottom billet surface, which is in contact with skid
$q_{\text{bottom},2}$	total flux for bottom billet surface, which is not in contact with skid
s	oxide scale thickness (m)
t	time (s)
ε_g	emissivity of the furnace gas mixture
ε_s	emissivity of the billet surface
ε_{g,CO_2}	emissivity of the CO_2 gas component
ε_{g,H_2O}	emissivity of the H_2O gas component
ε_{sw}	direct exchange factor
ε_w	emissivity of wall
$\Delta\varepsilon$	correction factor for gas mixture emissivity
τ_{gm}	mean gas transmissivity
λ	parabolic rate constant of oxidation (m^2/s)
σ	Stefan Boltzmann constant
ϕ_{sw}	view factor between billet surface and furnace wall
ρ	density (kg/m^3)
ρ_{os}	density of oxide scale (kg/m^3)
ρ_{st}	density of steel (kg/m^3)
γ	contact parameter (billet and skid) for a cell
θ	dimensionless temperature

Subscript

c	convection
g	gas of furnace
r	radiation
s	billet surface
sk	skid
st	steel
t	total
os	oxide scale
w	wall

Superscript

n	at time t
$n+1$	at time $t+\Delta t$

presented by Harish and Dutta [5]. They predicted radiative flux in the furnace and two dimensional temperature distributions in the billet. Jaklic et al. [6] studied the effect of space between the billets on walking beam furnace productivity. To perform this study they have developed a model by using Monte Carlo method for radiation heat transfer in the furnace and FDM for conduction heat transfer in the billet. There have been some recent efforts to simulate reheat furnace operation by means of commercial package FLUENT®. These models give heat flux distribution within the furnace that results in two dimensional temperature distributions in the slab or billet [7–9]. Jang et al. [10] presented a heat transfer model, which considers growing oxide layer. The model was used to predict heat flux distribution within the walking beam furnace and two dimensional temperature field in the billet during reheat. Han et al. [11,12] performed efficiency analysis and residence time optimization study of slab heating in the walking beam furnace. Dubey et al. [13] performed three dimensional transient heat conduction modeling by considering the growth of oxide scale on the billet surface during reheating. Dubey and Srinivasan [14] presented a parametric study, in order to investigate the effect of furnace gas zone temperature combinations on the responses of interest for the steel billet reheating process.

The above reviewed literature reveals that significant works have not been reported so far, for development of numerical model to predict the three dimensional temperature fields in the billet with growing oxide scale during reheat.