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Comparisons of different heat transfer models of a walking beam type reheat furnace☆

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ABSTRACT

Four different heat transfer models (Model-1 to -4) for the prediction of temperature of the slabs of a walking beam type reheat furnace have been compared. The models are classified based on the solution methodology and simplifications. In the first three models (Model-1 to -3), the furnace is modelled as radiating medium with spatially varying known temperature. Model-1 solves the 3D transient conduction in the slab and radiation in the furnace separately and is coupled via the boundary condition. In the second model, both radiation in the furnace and conduction in the slab are solved simultaneously. A user defined function (UDF) programme has been developed to process the movement of the slabs. Model-3 is similar to Model-2 but it includes additionally the skid support systems for the slabs. In the Model-4, convection in the furnace has been included in addition to all the features considered in Model-3. The convection has been modelled with the consideration of flow of hot gas through the inlet of the burners. All the models have been compared for their performance and computational time. Model-1 has been found to be quite economical and accurate. The inclusion of skid supporting system has little effect in the temperature distribution in the slab.

1. Introduction

The basic function of reheat furnace is to elevate the temperature of slab up to intended temperature while maintaining a uniform temperature in the slab with a temperature gradient not greater than 50 K/m at the exit of the furnace. The requirement of the uniform temperature distribution inside the slab at the exit of the furnace is important for the quality of steel. Although the heat transfer within the furnace includes all modes of heat transfer, it is mostly the radiative heat transfer which is dominant and over 90% of the heat transfer is via radiation [4]. Radiation emitted by hot gas and hot furnace walls is absorbed by the slabs. The absorbed radiation is converted into heat and this heat further penetrates inside the slabs by means of conduction.

The analysis of transient heating characteristic of the steel slabs in a reheating furnace has attracted considerable attention during the last few decades. Although there are limited studies available about the modelling of pusher type reheat furnace [1–3], most of the works in the recent past discuss about the modelling of walking beam type reheat furnace [1,4–6]. Numerical works were performed with simplified heat transfer model [3,6,7] as well as sophisticated CFD and combustion models [2,5,8]. In the simplified heat transfer models, only radiation heat transfer inside the furnace is considered. The radiation calculations are done using different radiation model like discrete ordinates [5], finite volume [3], radiosity [9] etc. with both grey gas [7] and non-grey gas radiation [3,8,10,11]. The steady state radiation in the furnace and transient conduction calculation in the slab were done separately and were coupled via boundary condition [3,6,7]. A few studies have been carried out in the recent past with CFD simulations [2,5,8] where both convection and radiation with fluid flow calculations are considered. Some of the studies are dedicated for different furnace geometries [10]. The movement of the slab in a walking beam type furnace is difficult to model and hence both the simulation in the furnace and in the slabs are done separately [3,6,7]. In the recent past, Han et al. [11] modelled this movement of slab by transferring the data of temperature from one slab to another at different time with a user defined function implemented in FLUENT. The advantage with this method is that the simulation can be done in a single integrated code of conduction and radiation and hence relatively more convenient for a user.

Recently, Han and Chang [12,13] carried out further analysis for walking beam furnace with combustion calculations. In one of their works [12], they carried out simulations for finding out the optimum residence time. In the other work [13], they have predicted the performance of an axial fired reheating furnace with the various fuel gas compositions.

It can be seen from the above literature review that although there are many models available, a comparison of different heat transfer models has not been addressed. It is important for a modeller to distinguish among the models in terms of their accuracy, complexity and computation efficiency. It is expected that the accuracy of a model should be good enough, but at the same time, it should not be at the cost of a huge computational power. It is important to have a reasonably accurate method which is computationally economical too.

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Nomenclature

C	specific heat of the slab (J/kg K)
I	radiation intensity (W/m^2 sr)
k	thermal conductivity (W/m K)
n	unit vector normal to the slab surfaces
Q	heat flux (W/m^2)
$\vec{r}$	position vector
$\vec{s}$	direction vector
t	time (s)
T	temperature (K)
x, y, z	Cartesian coordinates (m)

Greek symbols

ε	emissivity of slabs
θ	polar angle measured from the z-axis (rad)
κ	absorption coefficient [1/m]
ρ	density of the slab (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)
ϕ	azimuthal angle measured from the x-axis (rad)
Ω	solid angle (sr)

Superscripts

R	radiation

Subscripts

slab	Slab
w	Wall

The modelling of convection is also carried out in a different and simplified way in one of the models (Model-4) considered in this study than the available model in the existing literature where convective correlations were used.

Present work is based on developing and comparing four different models for predicting the transient heating characteristic of slab. In Model-1, the furnace was modelled for steady state radiation heat transfer using the discrete ordinates method available in the commercial software FLUENT [14]. A three-dimensional transient heat conduction code for heat transfer within slab was developed in MATLAB. The incoming radiative heat flux over slab's surfaces obtained from FLUENT simulation was used as boundary condition in the conduction code. The developed MATLAB code also accounts for outgoing radiative heat flux.

In Model-2, the furnace was modelled for transient conditions in FLUENT. The phenomena in the furnace are periodically transient because the slabs are transported toward a rolling mill at certain time intervals. Since FLUENT cannot process slab movement with its default function, a user-defined function (UDF) programme [15] in C language was developed and linked to FLUENT. This way both radiation in the furnace and transient conduction in the slab were simulated in FLUENT.

Model-3 includes the skid support system for the slabs in addition to all the features of Model-2. This skid support system blocks some part of radiation reaching to the slabs and hence it is important to see the effect of this blockage in the slab temperature. Solution procedure for Model-3 is exactly same as for Model-2.

In Model-4, furnace was modelled considering both radiation and convection inside the furnace and transient heat conduction inside the slab. This is done by introducing a mass flow inlet of hot gas at the burner's location. The flow rate of hot gas is kept equal to the total mass flow rate of fuel and air in a furnace. The temperature of hot gas was taken as approximately 85% of calculated adiabatic flame temperature. The rest of the methodology for this model is same as for Model-3.

2. Configuration of the furnace

Fig. 1(a) shows the half section of the walking beam type reheating furnace considered in this work. The furnace is symmetric along the $y = 0$ plane. The dimensions of the furnace are 5.4 m × 10.7 m × 36.0 m [10] and the furnace contains 27 slabs. The furnace is divided into three zones — preheating, heating and soaking. The preheating zone holds eleven slabs; the heating zone and soaking zone hold eight slabs each. Slabs are mostly heated in the preheating and heating zones. The role of soaking zone is to reduce the temperature gradient in the slabs.

A fresh slab is supplied from the left side wall of the furnace and transported step by step towards the exit. All slabs have the same dimensions and properties. The size of each slab is 0.23 m × 4.8 m × 1.0 m. Slabs are elevated 2.4 m from the furnace bottom and the distance between two slabs is 0.3 m. There are total 50 burners, out of which 24 burners are axial burner located in upper zone of furnace and 26 burners are transverse burners located in lower zone. The preheating zone contains eight axial burners and six transverse burners; heating zone contains eight axial and twelve transverse burners while soaking zone contain eight axial and eight transverse burners. The locations of the burners are only applicable for Model-4.

For Model-1, -2 and -3, the entire computational domain is divided into eight subzones to specify temperature distribution as shown in Fig. 1(b). Vertically, the entire domain is divided into two sections with respect to slabs. Horizontally, it is divided into four sections. Horizontal four sections are formed by splitting preheating zone into two sections, while other two zones remain unsplitted. Each subzone has constant wall and gas temperatures taken from Ref. [10]. The gas temperature is set to a value which is 200 K higher than the wall temperature. The emissivity of furnace wall is set to be 0.75. The density of slab is 7854 kg/m^3 and emissivity is 0.5. For Model-4, the temperature of the hot gas is 2050 K and mass flow rate in preheating heating and soaking zones are 13.376, 11.384 and 4.578 kg/s respectively.

3. Mathematical formulation

3.1. Model-1

The heat transfer within the slab is only by conduction. While the slabs move through the furnace their temperature continuously change as they are exposed to variable flux conditions which are different at different location of the furnace. The problem is, therefore, transient in nature with a time dependent flux boundary condition. The temperature field of the slab is governed by the following transient heat conduction equation

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

Here ρ, C and k are the mass density, specific heat, and thermal conductivity of the slab respectively. The boundary conditions for all the sides of the slabs are given as radiative boundary condition. The convective flux is neglected as the maximum heat transfer from the furnace to the slab is by radiation.

The following is the boundary conditions for all the faces of the slabs:

$$-k\frac{\partial T}{\partial n}\bigg|_{\mathrm{w}}=\varepsilon Q_{\mathrm{slab}}^{\mathrm{R}}-\varepsilon\sigma T_{\mathrm{w}}^{4} \tag{2}$$

In the above equation, $Q_{\mathrm{slab}}^{\mathrm{R}}$ is the incident radiation flux which is calculated from the radiation heat transfer analysis done in the