Applied Thermal Engineering 76 (2015) 496–508

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research paper

Assessment of uniform temperature assumption in zoning on the numerical simulation of a walking beam reheating furnace

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HIGHLIGHTS

- The heating process of steel slabs in a reheating furnace is numerically simulated.
- Unsteady calculations accounting for the periodic movement of the slabs are reported.
- We compare two models differing on how the thermochemical composition is obtained.
- The models predict mean slab temperatures at the exit that differ by less than 3%.
- The computational time of the fastest model is only about 5% of the slowest one.

ARTICLE INFO

Article history:
Received 16 January 2014
Accepted 21 November 2014
Available online 28 November 2014

Keywords:
Reheating furnace
Walking beam furnace
Slab heating
Mathematical modeling
Residence time
Skid mark

ABSTRACT

The numerical simulation of the heating process of steel slabs in a walking beam reheating furnace is reported using two different models. In one model, the turbulent reactive flow in the furnace is simulated together with the heat conduction in the slabs. The calculations are performed using a commercial code and a user-defined function is used to simulate the periodic movement of the slabs by the walking beams in the furnace. Unsteady calculations are performed until a periodic transient solution is achieved. In the second model, the furnace is divided into a small number of zones and the average temperature and chemical composition are prescribed in every zone based on the results of the first model. The unsteady heating process of the slabs is modeled using the same software and accounting for radiative transfer in the furnace and heat conduction in the slabs. The results of the first model are taken as a benchmark for the second one. It is shown that the first model predicts radiative heat fluxes and temperatures of the slabs that are consistent with previous work. The two models yield volume average temperatures of the slabs leaving the furnace that differ by less than 3%, provided that accurate values of the temperature of the gases and walls are used. The second model is computationally more economical, requiring only about 5% of the computational time of the first one.

1. Introduction

Reheating furnaces are used in the steel industry to heat steel slabs and increase their temperature above the recrystallization temperature for the subsequent plastic deformation in the rolling mill. Two different types of reheating furnaces may be distinguished, depending on how the slabs move along the furnace. In pusher type furnaces, the slabs move without any gap between them by means of a pusher mechanism, and they are supported by a skid system. In walking beam type furnaces, the slabs are moved by means of walking beams, and they are supported by fixed beams. In order to obtain finished steel plates of good quality, the temperature of the slabs leaving the furnace should be relatively uniform and close to a target temperature. Other important issues in the design and operation of reheating furnaces are the heating efficiency, the scale formation and the emission of pollutants.

Pusher typed reheating furnaces have been investigated by Mäkki et al. [1], who modeled the reactive fluid flow in a simplified geometry, Tang et al. [2] who included the skid rail support pillars in the simulation of the same furnace, and Harish and Dutta [3] who performed a coupled calculation of conduction in the steel billets and radiation in the gaseous medium. Many studies of walking

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http://dx.doi.org/10.1016/j.applthermaleng.2014.11.054
1359-4311/

beam type furnaces have been reported in the literature. Kim et al. [4,5] performed a 3D simulation of the reactive fluid flow in the furnace and calculated heat transfer by conduction in the slabs using a 2D approximation with measured temperatures and emissivities as boundary conditions. The influence of the distance between the billets was investigated in Ref. [6]. An improved heat transfer model is reported in Ref. [7], based on a coupled 2D finite volume method for both radiation and transient conduction in the slabs. This model was used to investigate the influence of the skid structure, residence time and furnace wall and slab emissivities [8], as well as the formation and growth of scale [9]. Han et al. [10] modeled the turbulent reactive flow in a bench scale reheating furnace, including radiation, along with the transient slab heating process. Han et al. [11] also extended to 3D a radiation/conduction model similar to that reported in Ref. [7], and used it to investigate the transient heating characteristics of the slabs. Then, the models for the fluid flow and radiation developed in Refs. [10,11] were coupled and an unsteady simulation was carried out taking into account the periodic movement of the slabs in the furnace [12]. Simplified versions of this model, in which the governing equations for the fluid flow were not solved and the heat transfer calculations were performed in 2D, were employed to study the efficiency of the furnace [13] and the influence of the fuel [14], while the full model was used to determine the optimum residence time of the slabs in the furnace [15].

Hsieh and co-workers [16–18] also simulated the reactive flow in the furnace and the transient heat conduction in the slabs, but they modeled the slabs as a fluid with very large viscosity that continuously flows along the furnace. In their first work, the temperature of the surface of the slabs was measured and used as a boundary condition for the heat conduction calculations in the slabs [16], while a coupled simulation was described in Ref. [17]. The latter formulation was used to investigate the influence of geometrical features of the skid supporting system on the skid marks [18].

Most of the works on walking beam furnaces reported in the literature have attempted to predict the temperature distribution in the slabs [5,7–18], which plays a major role in the quality of the final product, as stated above, and the heating efficiency of the furnace [4–6,13–18]. The energy consumption in a reheating furnace is quite significant, being the second most energy intensive process in the steel industry, only surpassed by the melting ore process. Accordingly, even small improvements in the heating efficiency are welcome, with the additional benefit of lower CO_2 emissions. Many factors influence the energy consumption, the heating efficiency and the temperature distribution in the slabs, such as, for example, the geometry of the furnace, including the burners and the walking beam system [8], the fuel [14], and the residence time of the slabs [3,8,11,15]. The emissivity of the slabs also plays an important role in the heat transfer process [7,8], since radiation accounts for more than 90% of the heat transferred to the slabs [4,7]. The scale has been much less studied [9]. The scale is the iron oxide layer that results from chemical reaction of the combustion gases with the hot surface of the steel slabs. The scale formation causes physical loss of the slab, and may significantly affect the heat transfer. The emission of pollutants in reheating furnaces has also received little attention in the literature. An exception is the work of Kim et al. [4], where the formation of NO_x was simulated.

The economical and environmental benefits of improvement in the design and operating conditions of reheating furnaces justify the efforts dedicated to investigate their performance, as reported in the works mentioned above. Most of these works have relied on mathematical models, since experiments are quite difficult to perform due to the large size of real furnaces, limited physical access and harsh environmental conditions in the furnace. Different types of mathematical models have been developed, but they may be broadly classified into two groups, namely models that prescribe the temperature and gas composition in the furnace or use a simplified approach to obtain those data, and models that solve the governing equations for the reactive flow field.

In the first group, the furnace is generally divided into a small number of zones and a uniform gas temperature is assumed in each zone based on limited experimental data [7–9,11]. However, it is also possible to apply mass and energy balances for every zone to determine the gas temperature in each zone [13,14]. The absorption coefficient may be taken as constant [7] or the gas composition of the medium is prescribed and its radiative properties evaluated using, in most cases, the weighted-sum-of-gray-gases model. The medium is often treated as gray, for simplicity reasons, even though a non-gray approach, which is more realistic and accurate, may be used [3,11,14]. Convection may be taken into account using either a fixed convection coefficient [8] or an empirical correlation [3], but is generally neglected in this group of models, since it is much less important than radiation. Conduction in the slabs is simulated using the finite-volume method in either 3D calculations [11] or a simplified 2D approach [7–9]. Radiative transfer may be calculated using the zonal [19,20] or the Monte Carlo [6] methods. However, most works use instead the discrete ordinates [16–18] or the finite volume [7–9] methods, which are much less time consuming and allow a more efficient coupling of conduction and radiation.

The slabs move along the furnace, being periodically displaced towards the exit to the rolling mill at constant time intervals. In most works this movement of the slabs is ignored, even though there is a coupling between radiative transfer in the furnace and transient heat conduction in the slabs. The coupled solution is needed because the heat transferred by conduction in the slabs depends on the heat flux incident on their surface, while radiation in the furnace depends on the temperature at the surface of the slabs, so that the two processes are coupled via the boundary condition at the surface of the slabs. The movement of the slabs is simulated in Refs. [12,15] by transferring the temperature of every slab to the downstream neighboring slab with a periodicity equal to that of the movement of the slabs. It is assumed that the slabs move instantaneously and do not disturb the fluid flow.

In the second group of models, the temperature and the chemical composition in the medium are calculated from the solution of the governing equations for the turbulent reactive flow in the furnace. In most past works, the $k-\varepsilon$ model was used for turbulence closure and a combustion model based on the transport of a conserved scalar with prescribed shape of the probability density function (pdf) was used for combustion, along with a fast chemistry approach [4,5,12,15–18]. Radiation in the furnace is calculated together with the reactive fluid flow simulation, and coupled with heat conduction in the slabs, as in the models of the first group.

A comparison of four different models has recently been reported [21]. Three of them belong to the first group. The simplest one ignores the movement of the slabs, and calculates radiative transfer only once. The incident radiative heat flux on the slabs is then used when solving the 3D transient heat conduction equation for the slabs during a time period equal to the residence time of the slabs in the furnace. The second model accounts for the transport of the slabs, and solves simultaneously in a coupled way for radiation in the furnace and heat conduction in the slabs, as described in Ref. [12]. The third model is identical to the second one, but the geometry of the furnace is more complex, since the walking beam supporting system is considered. The last model solves the governing equations for the fluid flow to estimate convective heat transfer, but does not model combustion, and still prescribes the