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Research Paper

Numerical simulation of fluid flow and heat transfer in an industrial continuous furnace

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HIGHLIGHTS

- A 3D, transient numerical study of an industrial continuous furnace is proposed.
- Geometry of furnace load is simplified by a thermally equivalent model.
- Load movement is avoided by implementing unsteady boundary conditions.
- Fairly accurate results at a reasonably low computational cost are obtained.

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ABSTRACT

We present a three-dimensional computational study of the transient heat transfer and turbulent fluid flow inside an arc-welding electrode continuous furnace. The model is implemented in FLUENT, a finite volume commercial code. Large difference in the length scales of the electrodes and the furnace, movement of the electrodes, and existence of various modes of heat transfer are the major factors influencing the accuracy and efficiency of the simulation. Two modeling strategies are used to overcome these difficulties. First, the electrode geometry and material composition are simplified using a thermally equivalent model. Second, the electrode movement inside the furnace is avoided by implementing time-dependent boundary conditions applied to a fixed domain. A fairly close agreement is obtained in comparing the load's temperature history against the experimental data with an absolute relative difference below 2.7%. The space between the electrode trays in the furnace is very limited. The analysis shows that the input air does not circulate effectively between the trays. This lowers the thermal efficiency of the furnace and leads to uneven treatment of the electrodes. The present study provides guidelines to improve future furnace designs.

1. Introduction

Arc welding electrodes play an important role in the construction of mechanical structures in various industries. Before the electrode is processed into its final state, it is usually heated in a furnace. The electrode is moved along the length of the furnace and, depending on the application, is thermally treated by various heat transfer mechanisms. This heat treatment is necessary to assure the quality of the welding and to ensure that all mechanical, metallurgical, environmental and economical measures are satisfied. The present paper aims at the performance evaluation of an industrial convective furnace, used to cure arc-welding electrodes. Five fans are employed to direct hot air, processed in a shell and tube heat exchanger, into the furnace.

Similar to many other applications of continuous furnaces [1–3], the load's temperature history has considerable importance in this case as well. However, because of the transient, multidimensional and turbulent flow conditions as well as existence of simultaneously different modes of heat transfer, it is hard to carry out an accurate, quick and inexpensive analysis. It has been shown that the preceding goals are achievable if Computational Fluid Dynamics (CFD) is employed [4,5]. Computational Fluid Dynamics provides an efficient tool to obtain the transient flow and temperature fields, to inspect the effects of thermo-physical and geometrical parameters on the curing process and to evaluate the success of various optimization methods. Furthermore, commercial CFD packages, such as FLUENT, CFX, STAR-CD or PHOENICS have increased the computational competency significantly and have

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Nomenclature

$c_{1\varepsilon}$, $c_{2\varepsilon}$, c_μ	constants in the k–ε model
c_p	specific heat capacity at constant pressure
h	convection heat transfer coefficient
κ	thermal conductivity
k	turbulent kinetic energy
n	outward unit normal vector
p	pressure
t	time
T	Temperature
u_i	velocity vector component (i = 1, 2, 3)
v	velocity magnitude
x_i	Cartesian coordinate component (i = 1, 2, 3)
ε	dissipation rate of turbulent kinetic energy
ρ	density
μ	viscosity
μ_t	turbulent viscosity coefficient
σ_k, σ_ε	turbulent Prandtl number for k and ε
φ	scalar

Subscripts

i,j	coordinate directions

Superscripts

–	Reynolds-averaged value
′	Reynolds fluctuation value

emerged as the dominant tools to perform quick numerical analysis with reasonable accuracy.

A detailed literature study shows that CFD tools have not yet been employed to analyze the transport phenomena inside an arc-welding electrode continuous furnace. However, reviewing similar applications of CFD for the study of continuous furnaces in steel [6], food [7] and ceramic [8] industries provides useful information for the analysis of electrode curing process. Almost all of the mentioned applications are followed by a standard methodology. First, the physical processes are described as mathematical models. Second, the governing equations are discretized and solved to obtain a numerical solution of the problem. Sensitivity analysis may then be conducted to evaluate the impacts of design and performance parameters on the simulation results. Here, use of Computational Fluid Dynamics with focus on commercial software in the numerical simulation of transport phenomena in steel reheat furnaces is briefly reviewed.

Prieler et al. [9] performed CFD modeling of an industrial walking hearth furnace to predict transient heating characteristics of the billets. Emadi et al. [10] obtained both convective and radiative heat fluxes using zone method and investigated the effects of design parameters on billet temperature behavior. Han and Chang [11] conducted a 3D unsteady numerical simulation of a reheat furnace with the commercial software FLUENT and analyzed the optimal slab residence time. Han et al. [12] carried out a periodically transient numerical simulation of heat transfer to slabs in a reheat furnace by using FLUENT. Due to the default software limitations a User-Defined Function (UDF) was developed to process the slab movement. Morgado et al. [13] followed a numerical strategy similar to that of Han [12] and compared two different thermochemical composition models for the slab. Dubey and Srinivasan [14] applied an unsteady three dimensional numerical model to analyze temperature field in the billet. They discretized the governing equations by finite volume method and solved the equations using an in-house MATLAB code. Kim et al. [15] presented a comprehensive FLUENT-based simulation to understand the turbulent flow and radiative heat transfer in a walking beam furnace. One of the significant implications of their work was the simplifications made in the modeling of the furnace geometry to avoid the unaffordable number of computational cells. Furthermore, other researchers conducted similar CFD studies using alternative software suits such as STAR-CD [16], Phoenics [17], FURMO [18] and CONCERT [19].

The current paper addresses a numerical approach, performed with FLUENT version 6.3 [20], to examine the non-isothermal flow phenomena inside an arc-welding electrode continuous furnace. Two important modeling strategies are employed here that are crucial to the success of the numerical approach and considerably reduce computational requirements of the simulation. To the best knowledge of the authors, these simplifying strategies have not been used by others for modeling arc-welding electrode continuous furnaces. First, we consider time-dependent boundary conditions to avoid the vastly expensive moving mesh methods required for modeling electrode movement inside the furnace. Instead of moving electrodes forward, we solve inside a fixed geometry (fixed segment of the furnace) and model the hot air inflow through time-dependent boundary conditions that move backward with the same velocity as the electrodes. Since FLUENT does not support moving boundary conditions with its default functions, a User Defined Function [21] is developed and linked to the main solver. Second, we replace the electrode geometry (cross-section) and material composition with a computationally inexpensive but thermally equivalent model. The existence of diverse length scales between the electrodes and the furnace renders the good quality grid generation and the efficient boundary condition implementation very challenging. Therefore, we propose several simplified models for the electrodes and systematically study them under equivalent furnace operating conditions.

Accuracy of the numerical results is verified by refining the computational grid to ensure that a grid independent solution is obtained, and by changing the time step used for the temporal discretization. In addition, the electrode's temperature history is compared to the experimental data obtained from a k-type thermocouple measuring the temperature in a real furnace operating condition. A maximum relative temperature difference below 2.7% is obtained which verifies the correctness of the simulation results and the assumptions used in the mathematical model.

The rest of the paper is organized as follows: The furnace and electrode configurations are described in Section 2. The mathematical and numerical models as well as the computational details are presented in Section 3. The results are discussed in Section 4 and, finally, Section 5 summarizes important conclusions.

2. Furnace configuration and arrangement of electrodes

The continuous electrode curing furnace considered here consists of preheating, heating and cooling sections that are 10, 9.8 and 4.7 m long, respectively. The electrodes pass through the entire furnace in 146 min with a velocity of 0.0028 m/s. Therefore, the electrodes are treated for 59.5, 58.5 and 28 min in each of the aforementioned furnace zones, respectively. Air is forced into the furnace through a number of nozzles, exchanges heat with electrodes and then leaves from the bottom. The first two sections