International Journal of Heat and Mass Transfer 103 (2016) 341–348

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer and thermo-elastic analysis of copper steel composite stave

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ARTICLE INFO

Article history:
Received 27 December 2015
Received in revised form 16 May 2016
Accepted 24 May 2016
Available online 3 August 2016

Keywords:
Blast furnace
Copper steel composite stave
Temperature
Thermal stress
Thermal deformation

ABSTRACT

This article investigates the thermal and deformational behavior in a copper steel composite stave for blast furnace process and analyzes the effects of copper layer thickness and reinforcing rib thickness on temperature, deformation and copper–steel interface thermal stress of copper steel composite stave. The model is validated by stave thermocouple data. The peak temperature of rib and brick hot-face are 177 °C and 966 °C, respectively. Copper steel composite stave deforms into the typical parabolic arc due to the expansion of the stave hot-face which is constrained by cool-face and furnace shell. A peak copper–steel interface stress, about 114 MPa, is found near the top or bottom border of the interface. Increasing reinforcing rib thickness and decreasing copper layer thickness are available in decreasing the thermal deformation and copper–steel interface stress of copper steel composite stave. The reinforcing rib thickness is found to be the most important for the stave thermal deformation behavior.

1. Introduction

The campaign life extension of a blast furnace is of a great concern issue in blast furnace operation and premature stave failure is one of the most important factors limiting campaign life, since a great investment is required to rebuild a furnace [1–5] Because of good thermal conductivity of pure copper, copper staves are generally installed at the high heat load region of a blast furnace, which is expected to elongate the campaign life of blast furnace up to over 15 years [6–8]. However, copper stave has experienced many problems and early failure, especially for the excessive deformation and water leakage [9,10]. It is very important to increase the anti-deformability of the copper stave and to improve the bonding strength between water pipe and the stave. Therefore, most researches focus on copper steel composite stave, due to its high bonding strength of pipe and stave, high anti-deformability, and good heat transfer performance.

Many mathematical models describe the heat transfer process and thermal stress distribution of the stave. Yeh et al. [11] developed a three-dimensional heat transfer model to predict the temperature distribution of a copper stave with different slag layer thickness. Qian et al. [12] used a 3-dimensional temperature field calculation model to investigate the quantificational indexes for design and evaluation of copper staves. Cheng et al. [13–15] carried out extensive research on heat transfer process of the stave by numerical simulation, studied the effect of blast furnace operation parameters and optimized the design parameters of the stave. Shi et al. [16,17] analyzed the reason leading to the deformation of copper stave from the thermal stress. Huan et al. [18] evaluated the thermal stress distribution of copper stave and analyzed the pipe welds failure problem in copper stave by the thermo-mechanical coupling. Zheng et al. [5,19] measured the overall heat transfer coefficient between the hot-face of copper stave and gas near the wall in experimental furnace and predicted the temperature distribution of the copper stave in the blast furnace. Liu et al. [20] investigated the water pipe failure problem of copper stave in blast furnace by thermal stress analysis. In spite of many investigations described above, these models only described the temperature and thermal stress distribution of copper stave. Liu et al. [21] investigated the transient heat transfer and thermal stress distribution of copper steel composite stave with or without accretion by thermal–mechanical coupled analysis. Lan et al. [22] later developed a three dimensional model to simulate the heat transfer and mechanical behavior in copper steel composite stave. Liu et al. [23] investigated the thermal stress distribution of copper steel composite stave without reinforcing rib and comparatively analyzed the heat transfer difference between copper steel composite stave, copper stave and cast steel stave. Xing et al. [24] analyzed the peak temperature of copper steel composite stave without reinforcing rib by oversimplified heat-transfer model. However,

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.100
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above models oversimplify important parameters such as furnace shell and reinforcing rib geometry. Therefore, previous models are unlikely to satisfactorily describe the complex heat transfer, thermal deformation behaviors of copper steel composite stave in blast furnace.

The present paper aims to shed some light on and deepen the understanding of heat transfer and thermal deformation behaviors in copper steel composite stave. A new three-dimensional mathematical model is presented to quantify copper steel composite stave temperature, deformation and copper–steel interface stress as a function of copper layer thickness and reinforcing rib thickness. The model is validated with stave thermocouple data.

2. Stave geometry

The main geometric features of the copper steel composite stave and reinforcing rib under consideration are shown in Fig. 1. The computational domain is the blast furnace wall, which is comprised of copper steel composite stave, reinforcing rib, packing and shell. The scale of computational domain is 1420 mm × 788 mm × 410 mm. Because of axial symmetry of blast furnace, only a piece of copper stave is modeled. Near the center of the copper steel composite stave, where a thermocouple set 30 mm from the hot face is inserted into the stave.

Each copper steel composite stave is cooled by four 63 mm equivalent diameter water pipes. Pure copper (T2) and carbon steel (20 g) are used to manufacture Cu/Fe composites. The Cu/Fe composites are obtained by means of the explosive cladding technique. The dimension of reinforcing rib is 1420 mm × 788 mm × 270 mm. The reinforcing rib which is made of 40 mm steel plates by welding is welded to the steel layer. Copper steel composite stave is bolted to the furnace shell with five bolts.

3. Mathematical model

3.1. Simplifications and assumptions

In order to shed some light on the complicated heat transfer process and thermal deformation behaviors in copper steel composite stave, the following simplifications and assumptions are introduced in the model.

(1) The heat transfer in copper steel composite stave is steady-state heat conduction.
(2) There is no gap at the interface between inlaid brick, packing layer and copper stave.
(3) The gas temperature near the working surface of the stave is uniform.
(4) No heat is generated in the blast furnace wall.
(5) The thermal deformation of packing and blast furnace shell are ignored.
(6) The thermal conductivity of the materials assumed to be constant in the x, y, z direction.
(7) Gravitational forces acting on the modeled system is neglected.

3.2. Heat-transfer model

The temperature of copper steel composite stave, T, is calculated by solving the steady heat conduction equation using nonlinear-temperature finite elements, since the thermal conductivity of the copper is dependent on temperature.

$$\frac{\partial}{\partial x}\left(\lambda(T)\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda(T)\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda(T)\frac{\partial T}{\partial z}\right)=0 \quad (1)$$

where $\lambda(T)$ is the thermal conductivity of the materials under different temperature, W m^{-1} °C^{-1}. The boundary conditions on each portion of the domain surface include:

1-A. The heat transfer between the stave and gas flow near the working face of blast furnace wall (boundary b1 in Fig. 1(b)) is the overall heat transfer comprised of convection and radiation, which can be described as follow:

$$\lambda(T)\frac{\partial T}{\partial N}\bigg|_{b1}=\alpha_f(T_f-T_{\text{hot-face}}) \quad (2)$$

where T_f is the gas temperature near the working face of blast furnace wall, °C; $T_{\text{hot-face}}$ is the hot face temperature of copper stave,°C; α_f is the overall heat transfer coefficient, W m^{-2} °C^{-1}; $\frac{\partial T}{\partial N}$ is the temperature gradient in normal direction on boundary, °C m^{-1}. The overall heat transfer coefficient at the working face of blast furnace wall can be determined by equation and [25]:

$$\alpha_f=0.62\left(\frac{\lambda_f}{D}\right)\left(\frac{DG}{\mu_f}\right)^{0.7}\left(\frac{C_p\mu_f}{\lambda_f}\right)^{1/3} \quad (3)$$

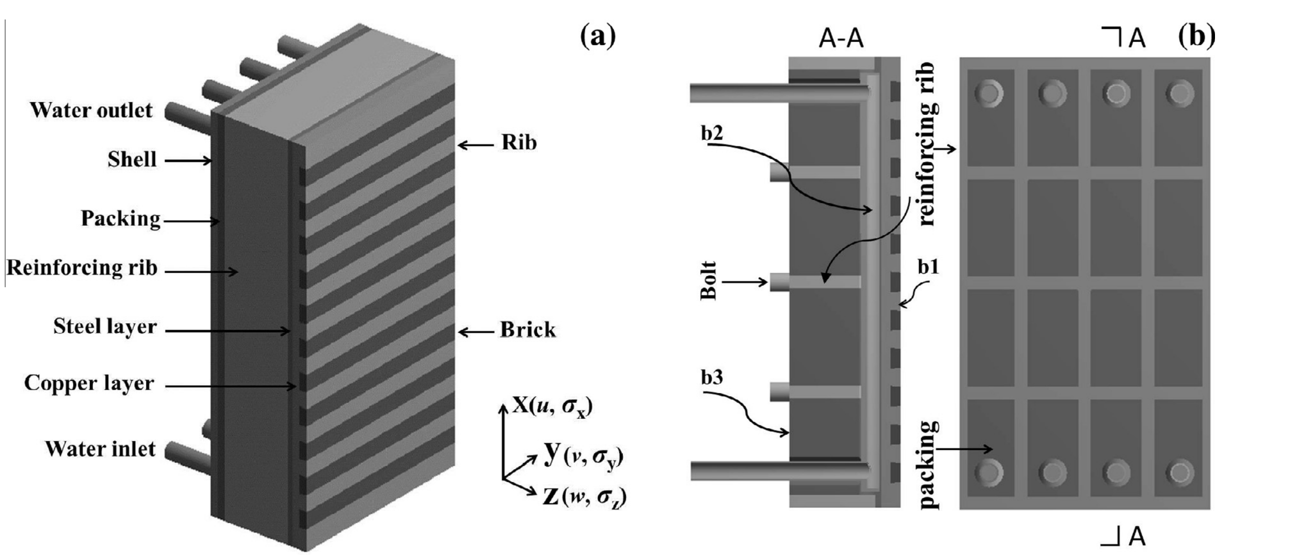

Fig. 1. Computational domain and reinforcing rib: (a) computational domain; (b) reinforcing rib. x—height; y—width; z—thickness.