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Heat transfer and thermal deformation analyses of a copper stave used in the belly and lower shaft area of a blast furnace

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ABSTRACT

This article describes a mathematical model to predict the temperature, thermal deformation and stress in a copper stave with no accretion layer during operation. The effects of gas temperature, cooling water velocity, copper stave thickness and bolt position on temperature, thermal deformation and stress of copper stave are investigated. The results show that a maximum temperature, about 422.5 K (149.5 °C), is found just near the top or bottom of the copper stave hot face. Copper stave deforms into the typical parabolic arc. Decreasing gas temperature can decrease the temperature, thermal deformation and stress, and decreasing the distance between the bolts and top or bottom border of copper stave are available in decreasing the copper stave thermal deformation, therefore improving the copper stave life. Increasing copper stave thickness can increase the temperature and thermal deformation for smaller copper stave thickness, while the thermal deformation in copper stave decreases with copper stave thickness increase for higher copper stave thickness. Water velocity has little effect on temperature and thermal deformation in copper stave, while much effect on the thermal stress around the root of the pipe.

1. Introduction

A long campaign life of copper staves in the belly and lower shaft region of the blast furnace is necessary for the ironmaking blast furnace since it ensures stable operation, which is a prerequisite of high productivity and long campaign life [1–3]. However, the early failure, especially the pipe welds failure, is one of key factors that cause the shortening of the copper stave campaign life [4]. Pipe welds can crack as a result of the thermal deformation of copper stave with large temperature gradient through its thickness, which causes water leaking through the copper stave. Damaged pipes are difficult to repair, and a replacement of a damaged copper stave from outside is practically impossible. The copper stave must be properly designed to withstand this deformation reliably without cracking, otherwise any water leaking would be a catastrophe. Therefore, it is important to have an in-depth understanding the heat transfer and thermal deformation of the copper stave.

Many studies have been carried out to describe the heat transfer and thermal deformation behavior of the copper stave. Yeh et al. [5] developed a three-dimensional heat transfer model to predict the temperature field of copper stave with different accretion layer thickness. Qian et al. [6] used a 3-dimensional temperature field calculation model to investigate the quantificational indexes for design and evaluation of copper staves. Cheng et al. [7–11] 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. [12] analyzed the reason caused the deformation of copper stave from the thermal stress. In spite of the many investigations described above, these models only described the temperature and thermal stress distribution of copper stave, and relatively less effort has been invested to understand the thermal deformation behavior of copper stave, which have higher Coefficient of thermal expansion compared to the conventional cast iron cooling stave. On the other hand, previous models often oversimplify important effects such as bolts, but their largest deficiency is oversimplification of the copper stave and blast furnace shell.

Further work is needed to quantify copper stave temperature and thermal deformation during operation as a function of operating conditions and design variables, such as gas temperature, cooling water velocity, copper stave thickness and bolt position with a new three-dimensional mathematical model. These are the aims of the current work.

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2. Model description

2.1. Physical system

The main geometric features of the copper stave and blast furnace wall under consideration are shown in Fig. 1. The blast furnace wall in the belly and lower shaft part of the furnace is generally comprised of refractory lining, copper stave, packing and shell. The computational domain and boundary conditions are shown in Fig. 1, where only a piece of copper stave is considered because of axial symmetry of blast furnace. The size of the computational domain is 2500 mm × 788 mm × 230 mm, and the thickness of the furnace shell, packing and copper stave is 30 mm, 80 mm, 120 mm, respectively. The equivalent diameter of cooling water channel is 60 mm. Copper stave is fixed at the furnace shell by a pin and four bolts. The thermal and thermomechanical properties of pure copper, steel, inlaid brick and packing layer are given in Tables 1 and 2, respectively.

2.2. Heat-transfer model

In order to shed some light on the complicated heat transfer process in the blast furnace wall, the following assumptions and simplifications are introduced in the model.

(1) The heat transfer in blast furnace wall is steady 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 furnace wall is uniform;
(4) No heat is generated in the blast furnace wall.

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

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

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

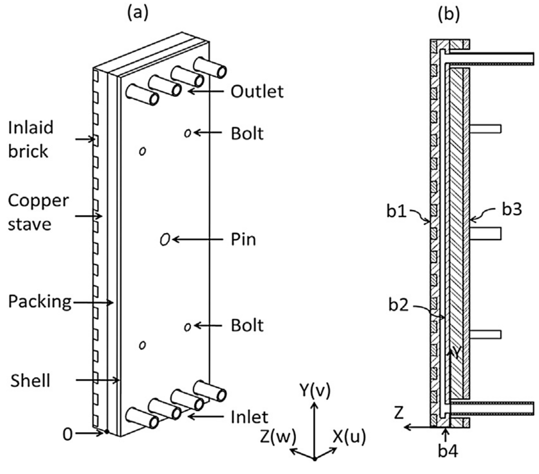

Fig. 1. Computational domain and boundary conditions: (a) computational domain; (b) cross-section of cooling channel in vertical. 0—Origin of coordinate; X—width; Y—height; Z—thickness.

Table 1
The coefficient of thermal conductivity of materials (W m^{-1} K^{-1}).

Temperature	Pure copper	Steel	Inlaid brick	Packing
273 K (0 °C)		55		
290 K (17 °C)	400			
293 K (20 °C)				0.35
373 K (100 °C)	380	52		
473 K (200 °C)		48		
573 K (300 °C)	365	45		
673 K (400 °C)			1.45	
973 K (700 °C)			1.50	
1373 K (1100 °C)			1.65	

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

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

where T_f is the gas temperature near the working face of blast furnace wall, K; $T_{hot\text{-}face}$ is the hot face temperature of copper stave, K; α_f is the overall heat transfer coefficient, W m^{-2} K^{-1}; $\partial T/\partial N$ is temperature gradient in normal direction on boundary, K m^{-1}. The overall heat transfer coefficient at the working face of blast furnace wall can be determined by equations (3) and (4) [13]:

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

$$D=\frac{2}{3}\frac{\varepsilon}{1-\varepsilon}(\phi d_p) \tag{4}$$

where λ_f is thermal conductivity of gas, W m^{-2} K^{-1}; μ_f is viscosity of gas, Pa s; ε is porosity of burden in blast furnace; $\varnothing$ is shape factor of burden particle; d_p is the diameter of particle in burden layer, m; D is the equivalent diameter of burden layer comprised of nonspherical particle, m; M is wall gas mass flowrate in blast furnace, kg s^{-1}.

1-B. The convective heat transfer at the interface between cooling water and the stave (boundary b2) can be described by the following equation:

$$-\lambda(T)\frac{\partial T}{\partial N}\bigg|_{b2}=\alpha_w(T_w-T) \tag{5}$$

where T_w is the average temperature of cooling water, K; α_w is the convective heat transfer coefficient between cooling water and stave body, W m^{-2} K^{-1}; the convective heat transfer coefficient α_w is dependent on the flowrate of cooling water velocity V for a given blast furnace, according to Titus–Boelt formula, the convective heat transfer coefficient is:

$$Re_f=\frac{Vd_e}{\nu_w} \tag{6}$$

$$Nu_f=0.023Re_f^{0.8}Pr^{0.4} \tag{7}$$

$$\alpha_w=\frac{\lambda_w}{d_e}Nu_f \tag{8}$$

where Re_f is the *Reynolds number*, ν_w is the kinematic viscosity of cooling water, m^2 s^{-1}; Nu_f is the *Nusselt number*; Pr is the *Prandtl*