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Numerical prediction on the erosion in the hearth of a blast furnace during tapping process ☆

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ABSTRACT

The erosion caused by mass transfer in hearth is the most important factor for determining blast furnace campaign life. To support a helpful insight information of mass transfer for the hearth of the No. 2 blast furnace at CSC (China Steel Corporation), a numerical model including the mass transfer of carbon in thermal convective flow from a blast furnace hearth has been developed during the steady tapping process (based on a uninterrupted tapping process assumption). The three dimensional Navier–Stokes equation combined with the transport equations of energy and species with conjugate heat transfer and physical dissolution source is solved by the finite control volume scheme subjected to the segregated iterate under propriety boundary conditions. The results showed the concentration distribution of carbon expressed in terms of mass flux for analyzing the erosion of carbon brick in the blast furnace hearth with the different conditions including the status of dead-man, production of liquid iron, carbon concentration at the inlet, and porosity distribution in coke zone during tapping process at steady state. The result is useful to mitigate the erosion caused by mass transfer, and prolong the life span of the blast furnace.

1. Introduction

The computational model of the erosion rate at the wall experimental relationships, depending on the velocity at the surface of carbon stick, was improved by Olsson et al. [1]. Further, the process of carbon dissolution is investigated in advance [2]. The results of their researches relate to the carbon source formed by iron flow, including the carbon brick and the coke in deadman.

In addition, Preuer et al. [3,4] numerically analyzed the influence of fluid flow during tapping-period, coke free and coke regions to modify the prediction of the erosion rate through the different degree of carbon dissolution in the different sections of the hearth experimentally. This model was developed more completely in 2003 [5]. There were more and more properties considered like as nature convection caused by temperature and concentration, viscosity and diffusivity of carbon in liquid iron flow in a two-dimensional model, and it made the simulative result more close to the reality. Consequently, we established a symmetrical three-dimensional domain of the hearth in the computational fluid mechanics (CFD) model based on the BF.2 of Chinese Steel Co (CSC) and cooperated with the on-line data. As to the research of the analyzing CSC BF.2, we extend the results of the previous study [6], and combined the real hearth model and CFD model to analyze liquid iron flow along the wall and carbon concentration depending on the furnace production, the situation of dead man, the porosity distribution of coke, production of liquid iron and carbon concentration at inlet, for evaluating the erosion rate in the hearth during tapping process at steady state. We expect that it will be useful to mitigate the erosion for the hearth according to these results, when changing the operating factor.

2. Physical system

In the present study, the BF 2 of CSC is taken as the physical model, including the solid zone (refractory) and fluid zone (deadman and coke-free zone) [6], displayed in Fig. 1 for the numerical simulation of the flow pattern, temperature, and carbon concentration to estimate erosion rate in the hearth of the blast furnace. According to the documents [7,8], the shape of designed deadman is described as a paraboloid. Due to the ratio of the depth (the distance from the taphole to the hearth bottom) and the diameter of hearth larger than 0.2 [9], the situations of the designed deadman are all floating. The other physical properties of the refractory refer to the previous publication [6].

3. Mathematic formulation

3.1. Conservation equations

The effects of nature convection, chemical reaction, and thermal radiation are not considered in this work. In addition, the 3D laminar and impressible hot fluid flow through porous free zone and porous coke as well as energy conservation with conjugated heat transfer between liquid and solid interfaces in a blast furnace during tapping

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Nomenclature

A_{sp}	Specific surface area (1/m)
C	Mass fraction of carbon (−)
C_p	Specific heat (J/kg K)
C_s	Saturated mass fraction of carbon (−)
$D_{C\text{–}Fe}$	Diffusivity of carbon into (liquid) iron (m^2/s)
D_p	Diameter of coke (m)
g	Gravity (m/s^2)
K	Mass convection coefficient (m/s)
K_0	Mass convection constant (m/s)
k_{eff}	Effective thermal conductivity in porous zone (W/m K)
k_{coke}	Thermal conductivity of coke (W/m K)
k_{iron}	Thermal conductivity of iron (W/m K)
m_c	Erosive mass flux from the hearth wall (kg/m^2 s)
P	Pressure (N/m^2)
S_u	Source term in momentum in porous zone see Eq. (3)
S_c	Source term in mass in porous zone see Eq. (8)
T	Temperature (°C)
V	Periphery velocity
$\vec{v}$	Superficial velocity (m/s)
v_0	Reference velocity (m/s)
x	x direction (m)
y	y direction (m)
z	z direction (m)
ε	Porosity (−)
μ	Viscosity (N/m s^2)
ρ	Density (kg/m^3)

are applied for examining metal fluid flow and carbon concentration in the hearth. The result in continuity, Navier–Stokes equation, energy and mass conservation at steady state can be written respectively:

$$\nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\nabla \cdot (\rho \vec{v}\vec{v}) = -\nabla P + \mu \nabla^2 \vec{v} + \rho \vec{g} + S_u \tag{2}$$

where, ρ (=7200 kg/m^3), P, $\vec{v}$, μ [5], and $\vec{g}$ are the density, pressure, the superficial velocity, the viscosity and the gravity. In the fluid zone, it was divided into two zones, coke-free zone and deadman. Thus, S_u is used to describe the momentum source in porous zone by the Ergun equation [10],

$$S_u = -150\mu \frac{(1-\varepsilon)^2}{\varepsilon^2 D_p^2} \vec{v} - 1.75\rho \frac{1-\varepsilon}{\varepsilon D_p} |\vec{v}| \vec{v} \tag{3}$$

In the Eq. (3), ε is the porosity, and D_p (=0.03 m) is the diameter of coke. In this model, there is no porous media in coke-free zone, and S_u is certainly zero in coke-free zone.

$$\nabla \cdot \left(\rho C_p \vec{v} T\right) = k_{eff} \nabla^2 T \tag{4}$$

Eq. (4) is the heat conservation in the hearth. In which, k_{eff}, T, and C_p are the effective conductivity, temperature, and the heat capacity (850 J/kg K).

$$k_{eff} = \varepsilon \times k_{iron} + (1-\varepsilon) \times k_{coke} \tag{5}$$

The effective conductivity shown as Eq. (5) in porous zone relates to porosity of dead-man in the hearth [11].

$$k_{coke} = (0.973 + 0.00634 \times T)\left(1 - \varepsilon^{2/3}\right) \tag{6}$$

The conductivity of carbon varies with temperature and porosity in the fluid zone, but the conductivity of iron is constant (=16.5 W/m-k) supposedly.

$$\nabla \cdot (\rho \vec{v} C) = \rho D_{C-Fe} \nabla^2 C + S_c \tag{7}$$

In this work, the mass conservation is expressed in Eq. (7).Where, $D_{C\text{-}Fe}$ is the diffusivity (=3×10^{-8} m^2/s) in this system. S_c is the mass source term which describe the carbon dissolving behavior in the deadman has shown in Eq. (8), where, K and A_{sp} defined in Eq. (9) are the mass convection coefficient and the specific area.

$$S_c = K\rho A_{sp}(C_s - C) \tag{8}$$

$$A_{sp} = \frac{6(1-\varepsilon)}{D_p} \tag{9}$$

The saturated carbon concentration is expressed in Eq. (10). On the other hand, S_c is zero in the coke-free zone.

$$C_s = 0.01 \times (1.35 + 0.00254 \times T) \tag{10}$$

In addition, the mass convection coefficient is defined as Eq. (11)

$$K = K_0 \times V^{0.7} \text{ and } V = \left(\frac{|\vec{v}|}{v_0}\right)[1] \tag{11}$$

where V is equal to the periphery velocity of the graphite cylinder, K_0 (=0.00053) is the mass convection constant, and periphery velocity is related to the velocity and reference velocity [5].

3.2. Boundary conditions

According to the average production in the BF 2 of CSC on April, May, and July in 2006, the production can be specified as 38, 43 and

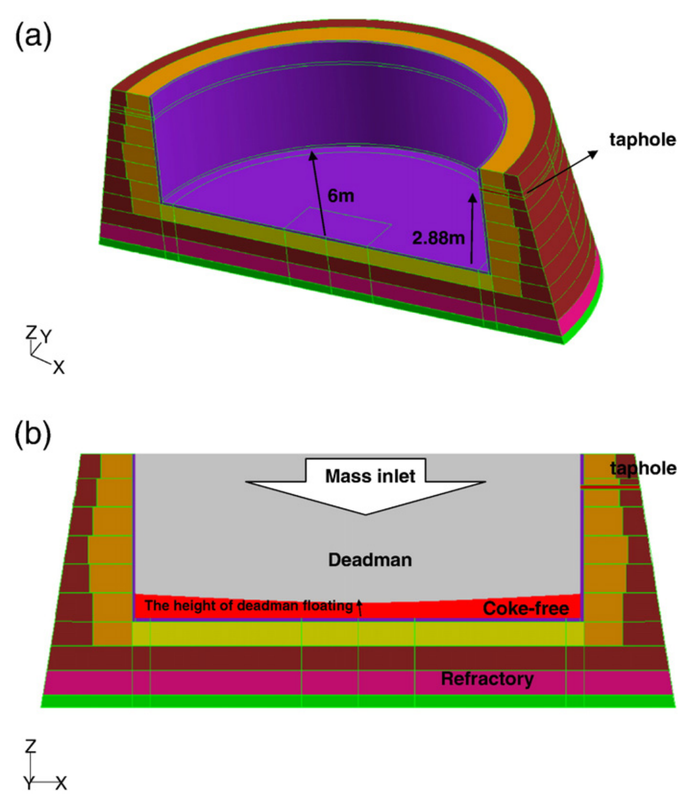

Fig. 1. (a) Geometric dimensions and refractory components of hearth, and (b) the diagram of solid zone and liquid zone in the hearth.