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CFD modeling of multiphase reacting flow in blast furnace shaft with layered burden

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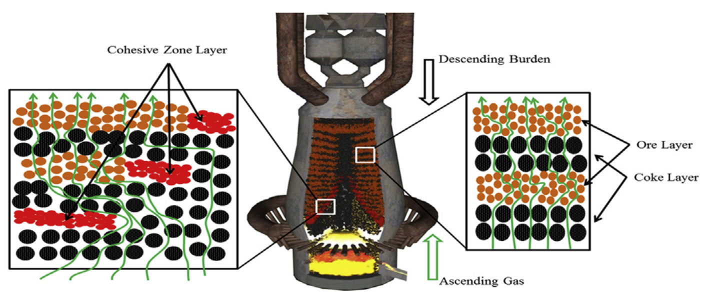
HIGHLIGHTS

- A novel methodology is proposed to efficiently model the blast furnace shaft with layered burden.
- The effects of layered burden on flow, heat transfer, and chemical reactions are considered in the model.
- The shape and location of the cohesive zone is determined by an iterative method.

GRAPHICAL ABSTRACT



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ABSTRACT

The ironmaking blast furnace is a counter-current chemical reactor which includes the ascending gas flow and the counter-current descending porous bed (burden). A Computational Fluid Dynamics (CFD) model has been developed to simulate the multiphase reacting flow in blast furnace shaft. The gas flow dynamics, burden movement, chemical reactions, heat and mass transfer between the gas phase and burden phase are included in the CFD model. The blast furnace burden consists of alternative layers of iron ore and coke. A novel methodology is proposed to efficiently model the effects of alternative burden layer structure on gas flow, heat transfer, mass transfer and chemical reactions. Different reactions and heat transfer characteristics are applied for difference types of layer. In addition, the layered CFD model accurately predicts the Cohesive Zone (CZ) shape where the melting of solid burden taking place. The shape and location of the CZ are determined by an iterative method based on the ore temperature distribution. The theoretical formation and the methodology of the CFD model are presented and the model is applied to simulate industry blast furnaces. The proposed method can be applied to investigate the blast furnace shaft process and other moving bed system with periodic burden structure configuration.

1. Introduction

The ironmaking blast furnace is regarded as the largest energy consumption metallurgical reactors to produce iron. The blast furnace is a counter-current moving bed reactor where the iron ore and coke are charged from the top to form the burden and the hot gas is generated at lower combustion zone. The blast furnace

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efficiency is directly depended on the heat and mass transfer to the ascending gas and descending burden. Due to the complicated phenomenon and difficulties indirect measurement, numerical models have been applied to simulate and understand the multiphase reacting flow inside the blast furnace [1–15].

In general, discrete and continuum models are the two major approaches to model the blast furnace moving bed. The Discrete Element Method (DEM) is applied to describe each individual ore and coke particle of the layered burden [14,15]. With coupling with the CFD for the gas phase, such simulation reveals the detail of the gas and particle behavior. However, it is computationally expensive due to the fact that blast furnace is a dense moving bed and the transient simulation is needed for DEM model [15]. On the other hand, the continuum approach assumes that the solid burden behave like a continuum medium. The existing blast furnace continuum models [3–8,10,12,13] treat the layered burden as a homogenous mixture of coke and ore. Therefore, the effects of layer thickness may not be reflected in the homogenous treatment for the burden. Kuwabara et al. [11] developed a 1D model that takes consideration of the layer structure and showed the effects of layer structure on gas distribution. The model neglects the variation in the furnace radius direction. In addition, the model assumed the coke temperature and ore temperature is the same therefore used one energy equation for the combination of coke and ore.

The coke and ore are alternately charged into the blast furnace to form a layered burden. The layer thickness is ranged from 0.2 to 0.8 m. The layer structure of the burden maintains up to the CZ and liquid iron and coke co-exists below the CZ. Usually there are about 30–60 layers of alternative coke layer and iron ore layer above the cohesive in blast furnace. The layer structure of the burden is important for furnace operation in the following aspects. First, the permeability differs significantly in the coke layer and ore layer. Second, different reactions are taken place for each type of layer, i.e., the reduction ($Fe_yO_x + CO \rightarrow Fe + CO_2$) takes place in iron ore layer and the coke gasification ($C + CO_2 \rightarrow 2CO$) takes place in coke layer. The reaction rates are directly related to the temperature of the individual layer. Pervious model assumed the ore and coke share the same temperature. The heat transfer and reaction heat are also differs from coke layer and ore layer. At last, the ore layer melts and becomes impermeable in the CZ so the coke layer is the only path that the gas can flow through. Dong et al. [2] concluded that the layered CZ treatment may provide a better overall picture of steady blast furnace operation in terms of the permeability prediction.

2. Model description

2.1. Model assumptions and simplifications

The following assumptions are made to derive the mathematic model.

1. The quasi-steady state approximation is assumed for the ascending gas phase due to the relative slow motion of the burden to the gas. It takes about 5 h for the burden to decent from the top to the bottom of the furnace but 2–3 s for the gas to flow from the bottom to the top [16].
2. The interface between the ore layer and coke layer is assumed thin so that the mix layer is neglected.
3. The layer structures remain until reaches the CZ lower boundary.
4. The layer volume maintains constant during burden descending.
5. The particles are connected in point so that the heat conduction between burden particles is neglected.

2.2. Governing equations

In the mathematical model, the ascending gas is described as the gas phase and the descending burden is treated as the burden phase (ore and coke). The burden phase is defined as the gross bed, i.e. the combination of the solid and liquid [1,10]. As state in assumption 1, the governing equations for the gas phase are quasi-steady state. The general transport equation for gas phase is given as Eq. (1).

$$\nabla\cdot\left(\rho_g \vec{\boldsymbol{u}}_{\mathbf{g}} \varnothing_g\right) = \nabla\cdot\left(\Gamma_g \nabla \varnothing_g\right) + S_g \tag{1}$$

For the solid phase, the diffusion term is zero because the transport of the solid phase properties is solely by convection (the movement of the burden). The general transport equation for burden phase is given as Eq. (2). The detailed conservation equations for gas phase and burden phase are expressed in Table 1. Two individual energy equations are used for the ore and coke due to the heat transfer and reactions are different in coke and ore layer.

$$\nabla\cdot\left(\rho_s \vec{\boldsymbol{u}}_{\mathbf{s}} \varnothing_s\right) = S_s \tag{2}$$

The gas flow through granular burden is described by Ergun type equation [17]. The potential flow model is adopted to describe the burden movement [1,4,9,10]. The mass conservation equation and momentum equation for the gas phase are combined to solve the pressure in the Poisson type equation as Eq. (3). Then the velocity is obtained by substituting the pressure into the momentum equation. Similarly, the same treatment is applied for the burden phase as Eq. (4). The coefficient K_s is the relative speed factor ranging from zero to unity.

$$\nabla\cdot\left(\rho_g K_g \nabla \mathrm{p}\right) = \dot{m_{o-g}} + \dot{m_{c-g}} \tag{3}$$

$$\nabla\cdot\left(\rho_s K_s \Phi_s\right) = -\dot{m_{o-g}} - \dot{m_{c-g}} \tag{4}$$

Because of the reaction heat and convective heat transfer differ in the coke layer and ore layer, two energy conservation equations are used, for coke and ore, respectively. The consideration of the burden structure on gas flow, heat transfer and chemical reactions are detailed in Section 2.4.

The boundary conditions are schematically shown in Fig. 1. At the furnace top, the top gas pressure P_{top} is set as a fixed value. The burden velocity distribution $v_s(r)$ along the radius is specified. The gradient of the gas enthalpy H_g and species mass fraction Y_i are assumed to be zero at the top outlet. The enthalpy of the ore $H_{o,top}$ and the enthalpy of the coke $H_{c,top}$ are set according to the charging material temperature. The concentrations of the burden $Z_{o,j,top}$ and $Z_{c,j,top}$ along the radius are obtained by combining the burden distribution and total charge rate. At the furnace bottom, the gas velocity, species mass fraction and gas enthalpy along the radius are mapped from the raceway model results [18]. The gradient of the coke enthalpy, ore enthalpy and burden composition is set as zero.

At the furnace side wall, the heat loss from the furnace shell is specified via the convection boundary condition where T_g is the gas temperature and T_∞ is the cooling water temperature (300 K). The effective heat transfer coefficient h_g includes the convection between the hot gas and the refractory, the conduction within the refractory, the conduction within the stave cooler, and the convection between the stave material and the cooling water. The actual value of h_g is difficult to determine analytically due to the complicated gas flow pattern and the erosion profile of the refractory. Therefore, h_g value is adjusted until the calculated total heat flux matches with the measured value. The gradient of all