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Model study of the effect of bird's nest on transport phenomena in the raceway of an ironmaking blast furnace

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ABSTRACT

Ironmaking blast furnace is an important reactor in extractive metallurgy. Understanding complex phenomena in the raceway region of an ironmaking blast furnace is important for high efficiency production. A three-dimensional CFD model is described to simulate the flow and thermochemical behaviours in the raceway region of blast furnace. It includes two fuels: pulverized coal and coke bed. The effect of bird's nest of coke bed is examined in terms of gas–particle flows and coal burnouts, where burnouts are investigated at two different locations, namely raceway endpoint and overall surface, respectively. It is found that the existence of bird's nest impacts the length of the jet and extension of the raceway. More importantly, bird's nest does not affect the coal burnouts at raceway endpoint much, but significantly affects the burnout over the raceway surface – lower burnout over the raceway surface when considering bird's nest in the simulations. The model provides an effective tool for understanding and optimizing the operation of a blast furnace.

1. Introduction

The blast furnace plays a dominant role in an integrated steelwork in terms of energy consumption and CO_2 emission (Ho et al., 2009; Ishii, 2000). A variety of minerals, such as iron ore in forms of sinter and pellet, coke, pulverized coal and flux (limestone), are involved in this process. In addition to adjusting the furnace operation from the burden, the lower part of blast furnace is also very important for adjusting furnace operation (Shen et al., 2006). As an important recent technology of adjusting furnace operation from lower part of blast furnace, pulverized coal injection (PCI) technology is widely used for economical, operational and environmental benefits such as reducing expensive coke consumption, adjusting furnace stability and reducing CO_2 emission. In this operation, pulverized coal is injected with gas into the lower part of blast furnace via a lance through a tuyere, and combusts in the raceway cavity and in the surrounding packed bed of coke solids (Fig. 1) (Mathieson et al., 2005). In PCI operation, high coal burnout is desired and necessary, allowing for high PCI rate operation; an appropriate distribution of gas composition is favourable for furnace stability. However, under increasingly higher PCI rate operation, the injected coal cannot burn completely inside the raceway and the unburnt char, together with the fine coke, may accumulate in the boundary of raceway, in particular beyond the end of raceway at the tuyere level, forming a low-permeability region, termed as bird's nest (Ishii, 2000). It may affect the furnace stability under severe conditions in terms of improper gas flow and low coal burnout (Kunitomo et al., 2004). But the effects from bird's nest on PCI operation were not well studied in the past studies. Therefore, it is important to investigate the effects of bird's nest on flow and combustion behaviours of coal particles in the lower part of blast furnace. It will provide practice guidance for process control and optimization.

The lower part of blast furnace is a very inaccessible region due to the unfriendly environment such as molten materials, high temperature and pressure, as well as abrasion caused by the descending phases of iron, slag and coke (Nightingale et al., 2000). The lower part of blast furnace associated with PCI operation, *i.e.* raceway region (from tuyere, raceway cavity and surrounding coke bed), can be studied by different methods. Full-scale investigations were employed such as dissection (Kanbara et al., 1977) and tuyere core drilling (Chung and Hur, 1997; Dong et al., 2007; Willmers, 1992) but they are extremely difficult due to the severe in-furnace environment and need a stoppage of the furnace operation. Experimental studies at laboratory- and pilot-scales can replicate the raceway region to a certain degree (Shen et al., 2008a) but is hard to replicate the in-furnace phenomena; moreover, they are rather expensive in terms of time and investment. As a result, only a few such attempts have been reported in the literature (Jamaluddin et al., 1986a). Alternatively, mathematical modelling, supported by physical experiments, provides an effective way to conduct parametric

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Nomenclature

A_1, A_2	pre-exponential factors of devolatilization reactions, s^{-1}
A_c	pre-exponential factors in Gibb model, $m\ s^{-1}\ K^{-1}$
A_p	particle area, m^2
A_s	constant in Gibb model, 0.0004
a	exponent in Gibb model, 0.75
C_0	mass of raw coal, kg
C_1, C_2	turbulent model constants
C_D	drag coefficient
C_p	particle heat capacity, $J\ kg^{-1}\ K^{-1}$
C_s	swelling coefficient
D	external diffusion coefficient of oxygen in Gibb model, $m^2\ s^{-1}$
D_{ref}	reference dynamic diffusivity in Gibb model, 1.8e−5 $kg\ m^{-1}\ s^{-1}$
daf.	dry and ash free
d_e	particle mean diameter, μm
e	void fraction of char particles
E_1, E_2	activation energy of devolatilization reactions, K
$\mathbf{f_D}$	drag force from a particle, N
H	enthalpy, $J\ kg^{-1}$
H_{reac}	reaction heat, $J\ kg^{-1}$
I	radiation intensity on particle surface, $W\ m^{-2}$
$[i]$	molar concentration of component i
k	turbulent kinetic energy, $m^2\ s^{-2}$
k_1,k_2	devolatilization rate constant, s^{-1}
k_1	rate of external diffusion in Gibb model, s^{-1}
k_2	rate of surface reaction rate in Gibb model, s^{-1}
k_3	rate of internal diffusion and surface reaction in Gibb model, s^{-1}
k_c	carbon oxidation rate in Gibb model, $m\ s^{-1}$
$\dot{m}$	mass transfer rate from a particle, $kg\ s^{-1}$
m_c	mass of char, kg
M_c	molecular weight of carbon
M_{O2}	molecular weight of oxygen molecule
n_p	particle number per unit volume, m^{-3}
Nu	Nusselt number
p	pressure, Pa
q	heat transfer from a particle, W
r_p	particle radius, m
r_i	reaction rate of gas species i, $mol\ m^{-3}\ s^{-1}$
Re	Reynolds number
T	temperature, K
T_{blast}	blast temperature, K
T_c	activation energy in Gibb model, K
T_{ref}	reference temperature in Gibb model, 293 K
T_s	constant in Gibb model, 6240 K
$\mathbf{U}$	mean velocity of gas, $m\ s^{-1}$
u, v, w	gas velocity components, $m\ s^{-1}$
VM	volatile matter of coal
v_i	stoichiometric coefficient of species i
W_i	reaction rate of species i (per unit volume), $kg\ m^{-3}\ s^{-1}$
m_a	ash mass fraction
$m_{a,0}$	original ash mass fraction

Greek letters

α	volume/internal surface area ratio in Gibb model
α_1, α_2	volatile yield
ε	turbulent dissipation rate, $m^2\ s^{-3}$
ε_p	particle emissivity
λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
σ_k, σ_ε	turbulence model constant
σ_B	Stefan–Boltzmann constant, $5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$
ϕ	mechanism factor in Gibb model
ρ	density, $kg\ m^{-3}$
μ	dynamic viscosity, Pa s
μ_t	turbulent viscosity, Pa s
Γ_i	molecular diffusivity of species i, $kg\ m^{-1}\ s^{-1}$

Subscripts

c	char
g	gas
p	particle

studies of PCI operation. For example, neural network was used as a black-box tool to understand the data from furnace operation and tuyere core drilling (Hao et al., 2005; Helle et al., 2009). But it cannot provide details of in-furnace phenomena in the lower part of blast furnace. Three-dimensional (3D) computational fluid dynamics (CFD) models integrating fluid flow and heat and mass transfers are needed for more practical problems. However, to date, only a few such 3D studies of bird's nest are found for the region of raceway-coke bed. Nogami et al. (2004) reported such a study focusing on the effect of blast temperature using a 3D transient-state model for a laboratory-scale test rig, where the reactions of both coal and coke were considered. Discrete element method (DEM) was also employed for coke solids movement so that the raceway structure could be predicted directly. This approach is generally difficult to apply to a practical system where the number of particles is huge and thus the computation will be expensive. For this reason, most PCI models are based on the continuum approach. Shen et al. (2009b,c,d) examined the effects of different operational conditions, such as coal size and volatile content, using a 3D pilot-scale PCI model of raceway only. All these model studies in lab- or pilot-scales could offer qualitative results to a certain degree. However, in these models, the flow and combustion features of pulverized coal were only investigated along the tuyere centreline. Moreover, the coke bed was not considered in these studies. In other words, the effects of bird's nest cannot be investigated in any details yet.

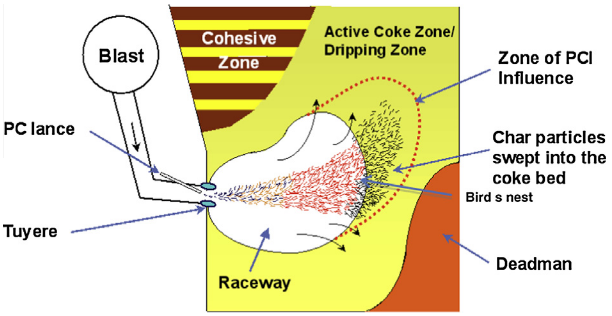

Fig. 1. Schematic of pulverized coal injection technology in a blast furnace.

To overcome these deficiencies, in this study, a recently developed 3D in-furnace model of pulverized coal combustion (Shen et al., 2011) is used for investigating the effects of bird's nest on in-furnace phenomena of PCI operation under practical conditions. The key flow and combustion characteristics are simulated. The impact of bird's nest is examined by comparing predictions