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Numerical study of hot charge operation in ironmaking blast furnace

S.B. Kuang [a,*], Z.Y. Li [a], D.L. Yan [b], Y.H. Qi [b], A.B. Yu [a]

[a] *Laboratory for Simulation and Modelling of Particulate Systems, School of Materials Science and Engineering, The University of New South Wales, Sydney, NSW 2052, Australia*
[b] *State Key Laboratory for Advanced Iron and Steel Processes and Products, Central Iron and Steel Research Institute, Beijing 100081, China*

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ABSTRACT

Charge of hot coke and iron-bearing materials into an ironmaking blast furnace (BF) may bring significant energy and environmental benefits to the BF process. However, there is little information about the quantitative effects of hot charge operation on BF flow and performance. This paper presents a numerical study of multiphase flow, heat and mass transfer in a BF by a process model. The applicability of the model in predicting BF performance is first confirmed by different applications. It is then used to study the effects of hot charge operation at different temperatures. The results are analyzed in detail with respect to BF flow and performance. It is shown that compared to the conventional operation, hot charge operation can lead to an increased productivity, decreased coke rate and CO_2 emission, and at the same time, increased gas pressure and top gas temperature. These effects vary with hot charge temperature.

1. Introduction

Blast furnace (BF) ironmaking is the most important technology by which iron is rapidly and efficiently reduced from iron-bearing materials (Biswas, 1981). Its primary energy source and reducing agent are mainly coal in form of coke and pulverized coal, which is finally released as CO_2 to the environment. Also, BF ironmaking system consumes 70% of the energy input in an integrated steelmaking works. Therefore, BF, as the core of the system, is usually featured with extensive energy consumption and massive greenhouse gas emission. Furthermore, such a reactor demands a significant amount of coke to maintain adequate furnace permeability and provide thermal and chemical energy sources. The consumed coke, as a kind of noble material, shares a large portion (~25%) of the production cost of hot metal (HM). As such, coke rate (coke consumption per tonne of hot metal, also referred to as CR for convenience) is critical to BF performance with regard to energy efficiency, CO_2 emission and production cost.

In recent years, various technologies have been developed to improve BF performance. These include, for example, top gas recycling (Austin et al., 1998; Nogami et al., 2006; Chu and Yagi, 2010; Helle et al., 2010), injection of pulverized coal, hydrogen bearing materials, natural gas, and coke oven gas (Slaby et al., 2006; Li et al., 2007; Shen et al., 2009), charge of novel burden materials such as scrap and carbon composite agglomerate (Nogami et al., 2006; Kawanari et al., 2011), and hot charge (Biswas, 1981). Although being examined at various levels, many of these technologies are still on trial, with the long-term practical feasibility largely remaining unknown. This is especially true for hot charge operation, where coke and iron-bearing materials, usually referred to as burden, are alternatively charged into a BF at a higher temperature than the ambient temperature as used in a conventional operation. This high temperature may be achieved through the following two ways. One directly charges the hot stock materials from the upstream of the BF, which avoids the massive energy loss related to cooling process. Another makes use of the unutilized sensible heat and chemical energy of materials within the integrated steelmaking works to preheat the burden materials to a certain temperature before charging. With the help of the extra heat input from the furnace top, hot charge operation may have great potential in improving BF performance. However, to date, our knowledge about the effect of such a technology on BF flow and performance is little, especially at a quantitative level. This problem is further complicated by the fact that conveying and charging systems required by hot charge operation to withstand the high temperature environment at the furnace top have not been fully established yet.

On the other hand, in order to secure a successful running of new operations, it is a necessary prerequisite to predict and understand BF flow and performance over a wide range of conditions. This is difficult to achieve experimentally, because ironmaking BF is a very complex multiphase reactor accompanying with high temperature and hazardous conditions. In principle, this problem can be overcome by numerical simulation. In this direction, various mathematical models have been developed in the past decades to describe localized or global particulate and multiphase flow behaviors in BFs (see, for example, the recent review by Dong et al.

* Corresponding author. Tel.: +61 2 9385443; fax: +61 2 93856565.
E-mail address: s.kuang@unsw.edu.au (S.B. Kuang).

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Nomenclature

a_{Feo}	activity of molten wustite
A_c	effective surface area of coke for reaction, m^2
c_p	specific heat, $J\ kg^{-1}\ K^{-1}$
d	diameter of solid particle, m
$D^e_{g,CO}$	effective diffusivity of carbon monoxide, $m^2\ s^{-1}$
E_f	effectiveness factors of solution loss reaction
f_o	fraction conversion of iron ore
$\boldsymbol{F}$	interaction force per unit volume, $kg\ m^{-2}\ s^{-2}$
$\boldsymbol{g}$	gravitational acceleration, $m\ s^{-2}$
h_{ij}	heat transfer coefficient between i and j phases, $W\ m^{-2}\ K^{-1}$
H	enthalpy, $J\ kg^{-1}$
ΔH	reaction heat, $J\ kg^{-1}$
k	thermal conductivity, $W\ m^{-1}\ K^{-1}$
k_f	gas-film mass transfer coefficient, $m\ s^{-1}$
k_i	reaction constant of ith chemical reaction, $m\ s^{-1}$
K_1	equilibrium constant of indirect reduction of iron ore by CO
M_i	molar mass of ith species in gas phase, $kg\ mol^{-1}$
M_{sm}	molar mass of FeO or flux in solid phase, $kg\ mol^{-1}$
p	pressure, Pa
pct	percentage
p_r	prandtl number, $c_p\ \mu K^{-1}$
R^*	reaction rate, $mol\ m^{-3}\ s^{-1}$
S	source term
Sh_r	shrinkage ratio defined as the ratio of the decreased volume, caused by softening and melting, to the original volume occupied by iron-bearing material
Sh_r^*	normalized shrinkage ratio, $Sh_r^* = Sh_r/Sh_{r,\max}$, $Sh_{r,\max} = 0.7$
T	temperature, K
$\boldsymbol{u}$	interstitial velocity, $m\ s^{-1}$
V_b	bed volume, m^3
V_g	gas volume, m^3
Vol_{cell}	volume of control volume, m^3
y_i	mole fraction of ith species in gas phase
y_i^*	mole fraction of ith species in equilibrium state

Greek letters

Γ	diffusion coefficient
$\boldsymbol{I}$	identity tensor
ϕ	general variable
Φ	shape factor
α	specific surface area, $m^{-2}\ m^{-3}$
β	mass increase coefficient of fluid phase associated with reactions, $kg\ mol^{-1}$
δ	distribution coefficient
ε	volume fraction
η	fractional acquisition of reaction heat
μ	viscosity, $kg\ m^{-1}\ s^{-1}$
ρ	density, $kg\ m^{-3}$
$\boldsymbol{\tau}$	stress tensor, Pa
ω	mass fraction
ξ_{ore}, ξ_{coke}	local ore, coke volume fraction

Subscripts

e	effective
g	gas
i	identifier (g or s)
i, m	mth species in i phase
j	identifier (g or s)
k	kth reaction
s	solid
sm	FeO or flux in solid phase

Superscripts

e	effective
g	gas
s	solid

(2007)). Generally speaking, the existing approaches can be classified into two categories: continuum approach at a macroscopic level and discrete approach at a microscopic level. The former is suitable for process modelling and applied research because of its computational convenience and efficiency. Indeed, most of the BF modelling is based on continuum approach (Dong et al., 2007). However, to date, comprehensive numerical studies of hot charge operation in BF have not been found in the literature.

This paper presents a numerical study of BF flow and performance at different hot charge temperatures by a continuum-based process model. It is organized as follows. First, the numerical model is introduced. The applicability of the model is examined by different applications. On this base, the effects of hot charge on process performance are quantified, followed by a detailed study of the flow and heat and mass transfer for better understanding. The findings from this study should be useful not only for establishing a full picture about the hot charge operation but also for developing some guides for possible implementation of this technology in practice.

2. Model description

The current BF process model is a two-dimensional (2-D) mathematical model which considers mass, momentum and enthalpy conservations for gas and solid phases at steady state. It is in principle the same as that recently reported by Dong et al. (2010). For brevity, we only describe the key features of this model below, with the new developments emphasized.

2.1. Governing equations

Table 1 summarizes the governing equations for fluid flow as well as heat and mass transfer considered in this study. Gas is described by the well-established volume-averaged, multiphase, Navier–Stokes equations (Dong et al., 2007). Solids are assumed to be a continuous phase that can be modelled based on the typical viscous model used in multiphase flow modelling (Austin et al., 1997), coupled with the method proposed by Zhang et al. (1998) for determination of the deadman boundary. General convection–diffusion equations are applied to describe heat and mass transfer among the phases.

2.2. Momentum, heat and mass transfer between phases

The gas–solid interaction as gas flows through a packed bed is described by the Ergun's expression (1953):

$$\boldsymbol{F}_g^s = -\boldsymbol{F}_s^g = -(\alpha_f \rho_g |\boldsymbol{u}_g^s| + \beta_f)\boldsymbol{u}_g^s. \quad (1)$$

The interphase mass transfer, which occurs due to reactions and phase changes, is evaluated from simple mass balances. Accordingly, three crucial chemical reactions and two important phase