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# Analysis of gas–solid flow and shaft-injected gas distribution in an oxygen blast furnace using a discrete element method and computational fluid dynamics coupled model

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ABSTRACT

Ironmaking using an oxygen blast furnace is an attractive approach for reducing energy consumption in the iron and steel industry. This paper presents a numerical study of gas–solid flow in an oxygen blast furnace by coupling the discrete element method with computational fluid dynamics. The model reliability was verified by previous experimental results. The influences of particle diameter, shaft tuyere size, and specific ratio ($X$) of shaft-injected gas (SIG) flowrate to total gas flowrate on the SIG penetration behavior and pressure field in the furnace were investigated. The results showed that gas penetration capacity in the furnace gradually decreased as the particle diameter decreased from 100 to 40 mm. Decreasing particle diameter and increasing shaft tuyere size both slightly increased the SIG concentration near the furnace wall but decreased it at the furnace center. The value of $X$ has a significant impact on the SIG distribution. According to the pressure fields obtained under different conditions, the key factor affecting SIG penetration depth is the pressure difference between the upper and lower levels of the shaft tuyere. If the pressure difference is small, the SIG can easily penetrate to the furnace center.



## Introduction

According to the International Energy Agency (2007), the iron and steel sector accounts for about 5% of the world's total $CO_2$ emissions. Iron and steel enterprises must respond to strict regulations on carbon emissions by actively developing new technologies. Use of the oxygen blast furnace (OBF) was initially proposed by Wencel (1970) as an improved blast furnace (BF) ironmaking process. Scholars from around the world have subsequently proposed various different improved OBF processes (Fink, 1996; Lu & Kumar, 1984; Ma & Edstrom, 1992). The main characteristics of such processes are full oxygen injection, top gas recycling (carbon cycle), shaft gas injection, replacement of coke by pulverized coal, and high productivity. Some industrial trials have been carried out, including those of the ultra-low $CO_2$ steelmaking process in Europe (Danloy et al., 2009; Meijer et al., 2009; Zuo & Hirsch, 2009) and experimental OBFs in Japan (Miwa & Kurihara, 2011; Ohno, Matsuura, Mitsufuji, & Furukawa, 1992) and Russia (Tseitlin, Lazutkin, & Styopin, 1994). These industrial tests demonstrated the feasibility and effectiveness of the OBF ironmaking process. There is, however, little fundamental research on the in-furnace phenomena in OBFs, especially those of the gas–solid flow and shaft-injected gas (SIG) penetration behavior. New modeling methods enable investigations of these behaviors.

The discrete element method (DEM) was first proposed by Cundall and Strack (1979) and was then rapidly developed by subsequent scholars. Ariyama et al. (2014) provided a review of advanced BF mathematical models based on DEM. This method has been applied to simulate the BF burden distribution (Zhang et al., 2014) and solid flow in furnaces (Zhou et al., 2005). Particles in almost any industrial system are subjected to a drag force from the external fluid (gas or liquid); in such cases, coupling of DEM with computational fluid dynamics (CFD) (Zhou, Zhu, Wright, Yu, & Zulli, 2011; Zhou, Zhu, Yu, Wright, & Zulli, 2008) is the best way to study gas–solid flow behavior in these multiphase flow systems.

Injection of a reducing gas through the shaft tuyere is one of the most important features of the OBF process and plays crucial roles in the heat balance, reduction potential, and development of indirect reduction in the shaft (lump) zone (Han, Xue, & Li, 2010). Studies on the penetration of the SIG have been carried out using different methods. The cold model (Liu, Xue, She, & Wang, 2014) and DEM–CFD coupled model (Natsui et al., 2011a, 2011b) are

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**Table 1**
Forces and torques acting on particle $i$.

| Forces and torques | Symbols | Equations |
|---|---|---|
| Normal contact force | $\mathbf{F}_{\mathrm{cn},ij}$ | $-2/3S_\mathrm{n}\lvert\boldsymbol{\delta}_\mathrm{n}\rvert\mathbf{n}$ |
| Normal damping force | $\mathbf{F}_{\mathrm{dn},ij}$ | $-2\sqrt{5/6}\beta\sqrt{S_\mathrm{n}m^*}\mathbf{v}_{\mathrm{n},ij}$ |
| Tangential contact force | $\mathbf{F}_{\mathrm{ct},ij}$ | $-S_\mathrm{t}\lvert\boldsymbol{\delta}_\mathrm{t}\rvert\mathbf{t}$ |
| Tangential damping force | $\mathbf{F}_{\mathrm{dt},ij}$ | $-2\sqrt{5/6}\beta\sqrt{S_\mathrm{t}m^*}\mathbf{v}_{\mathrm{t},ij}$ |
| Coulomb friction force | $\mathbf{F}_{\mathrm{t},ij}$ | $-\mu_\mathrm{s}\lvert\mathbf{F}_{\mathrm{cn},ij}+\mathbf{F}_{\mathrm{dn},ij}\rvert\mathbf{t}$ |
| Torque by tangential forces | $\mathbf{M}_{\mathrm{t},ij}$ | $R^*\mathbf{n}\times(\mathbf{F}_{\mathrm{ct},ij}+\mathbf{F}_{\mathrm{dt},ij})$ |
| Rolling friction torque | $\mathbf{M}_{\mathrm{r},ij}$ | $-\mu_\mathrm{r}\lvert\mathbf{F}_{\mathrm{cn},ij}+\mathbf{F}_{\mathrm{dn},ij}\rvert R\hat{\boldsymbol{\omega}}_i$ |

Where: $S_\mathrm{n}=2E^*\sqrt{R^*\lvert\delta_\mathrm{n}\rvert}$, $\boldsymbol{n}=\frac{\delta_\mathrm{n}}{\lvert\delta_\mathrm{n}\rvert}$, $\frac{1}{m^*}=\frac{1}{m_i}+\frac{1}{m_j}$, $\beta=\frac{\ln e}{\sqrt{\ln^2 e+\pi^2}}$, $S_\mathrm{t}=8G^*\sqrt{R^*\delta_\mathrm{n}}$,

$\boldsymbol{t}=\frac{\boldsymbol{\delta}_\mathrm{t}}{\lvert\delta_\mathrm{t}\rvert}$, $\frac{1}{E^*}=\frac{1-\upsilon_i^2}{E_i}+\frac{1-\upsilon_j^2}{E_j}$, $\frac{1}{R^*}=\frac{1}{\lvert\mathbf{R}_i\rvert}+\frac{1}{\lvert\mathbf{R}_j\rvert}$, $\frac{1}{G^*}=\frac{2(1+\upsilon_i)(1-\upsilon_i^2)}{E_i}+\frac{2(1+\upsilon_j)(1-\upsilon_j^2)}{E_j}$

$\boldsymbol{v}_{\mathrm{n},ij}=(\boldsymbol{v}_{ij}\cdot\boldsymbol{n})\cdot\boldsymbol{n}$, $\boldsymbol{v}_{\mathrm{t},ij}=(\boldsymbol{v}_{ij}\cdot\boldsymbol{t})\cdot\boldsymbol{t}$, $\hat{\omega}_i=\frac{\boldsymbol{\omega}_i}{\lvert\omega_i\rvert}$, $\boldsymbol{v}_{ij}=\boldsymbol{v}_j-\boldsymbol{v}_i+\boldsymbol{\omega}_j\times\boldsymbol{R}_j-\boldsymbol{\omega}_i\times\boldsymbol{R}_i$,

$E^*$, $\boldsymbol{\delta}_n$, $m^*$, $R^*$, $G^*$, $S_\mathrm{t}$, and $e$ mean the equivalent Young's modulus, normal amount of overlap, equivalent mass, equivalent radius of the particles, coefficient of restitution, equivalent shear modulus, and tangential stiffness of particles, respectively.

available for studying the SIG penetration behavior in an OBF. Factors affecting SIG radial penetration along the shaft include burden resistance, blast kinetic energy, and gas inertia force confrontation between the horizontal SIG and the rising gas. The effects of SIG flowrate, furnace profile, and shaft tuyere position on SIG penetration have been studied previously (Liu et al., 2014; Natsui et al., 2011a, 2011b), but the specific manifestations of these factors differ in ways that merit further research. For example, the blast kinetic energy is determined by the gas flowrate or the area of the shaft tuyere inlet. In previous studies, certain factors, especially burden characteristics, such as particle diameter and shaft tuyere size, were not taken into account: previous researchers (Natsui et al., 2011a, 2011b) usually employed the manner in which hearth and shaft tuyeres inject the same kinds of gases to evaluate SIG penetration behavior by observing its effects on the gas pressure distribution, gas–solid drag force, or gas velocity. This approach can reveal some SIG penetration characteristics but is limited. There is little reported concerning solid flow characteristics in OBFs.

In this paper, these unresolved issues were further studied using a different method; some new factors influencing gas flow were also considered. The method used in this work was similar to that of our previous down-scaled cold model study (Liu et al., 2014); i.e., different kinds of gases are blown into the hearth and shaft tuyeres to quantitatively and accurately analyze the SIG penetration behavior. Here, we used an equal-scaled DEM–CFD coupled model to investigate the solid flow and SIG penetration behavior in an OBF. Factors influencing SIG penetration, such as particle diameter, shaft tuyere size, and specific ratio ($X$) of the SIG flowrate to total gas flowrate, were evaluated and the most significant factor identified. We hope that this work will provide some valuable theoretical data for further optimization of OBF operating parameters and design.

## Model description

### *Discrete element method*

*EDEM* commercial software (EDEM$^{\mathrm{TM}}$, England) was used to describe the particle flow behavior. A single particle in a granular system undergoes translational and rotational motions that are described by Newton's second law of motion. The model consists of a spring and dashpot in the normal direction, and a spring, dashpot, and slider in the tangential direction (Mindlin & Deresiewicz, 1953). At any time $t$, the governing equations for particle $i$ can be written as follows:

$$m_i\frac{d\mathbf{v}_i}{dt}=\sum\nolimits_j(\mathbf{F}_{\mathrm{cn},ij}+\mathbf{F}_{\mathrm{dn},ij}+\mathbf{F}_{\mathrm{ct},ij}+\mathbf{F}_{\mathrm{dt},ij})+m_i\mathbf{g}+\mathbf{F}_{\mathrm{pf},i},\tag{1}$$

**Table 2**
Particle properties and conditions used in this work.

| Variables | Base values |
|---|---|
| Particle shape | Spherical |
| Number of particles | Variable |
| Particle diameter (mm) | Variable |
| Coke particle density (kg/m$^3$) | 1100 |
| Ore particle density (kg/m$^3$) | 4000 |
| Wall density (kg/m$^3$) | 7600 |
| Material Poisson's ratio | 0.25 |
| Material shear modulus (Pa) | $1.0\times10^8$ |
| Particle–particle restitution coefficient | 0.3 |
| Particle–particle static friction coefficient | 0.4 |
| Particle–particle rolling friction coefficient | 0.05 |
| Particle–wall restitution coefficient | 0.3 |
| Particle–wall static friction coefficient | 0.4 |
| Particle–wall rolling friction coefficient | 0.05 |
| DEM time step (s) | $5\times10^{-5}$ |

$$I_i\frac{d\boldsymbol{\omega}_i}{dt}=\sum\nolimits_j(\mathbf{M}_{\mathrm{t},ij}+\mathbf{M}_{\mathrm{r},ij}),\tag{2}$$

$$I_i=0.4m_iR^2,\tag{3}$$

where $m_i$, $\mathbf{v}_i$, $\boldsymbol{\omega}_i$, and $R$ are the mass, translational velocities, rotational velocities, and radius of particle $i$, respectively. $I_i$ is the moment of inertia of particle $i$, which is given by $I_i=0.4m_iR^2$. The forces involved are: the particle–fluid interaction force, $\mathbf{F}_{\mathrm{pf},i}$; the gravitational force, $m_i\mathbf{g}$; and the contact forces between the particles and between the particles and walls. Specifically, the contact forces include those in the normal and tangential directions, $\mathbf{F}_{\mathrm{cn},ij}$ and $\mathbf{F}_{\mathrm{ct},ij}$, and the damping forces in normal and tangential directions, $\mathbf{F}_{\mathrm{dn},ij}$ and $\mathbf{F}_{\mathrm{dt},ij}$. The torque acting on particle $i$ includes two components: $\mathbf{M}_{\mathrm{t},ij}$, which is generated by the tangential force and causes particle $i$ to rotate, and $\mathbf{M}_{\mathrm{r},ij}$, commonly known as the rolling friction torque, which is generated by the normal force and slows down the relative rotation between particles. The forces and torques used in the model are listed in Table 1. Note that when the sum of $\mathbf{F}_{\mathrm{ct},ij}+\mathbf{F}_{\mathrm{dt},ij}$ is larger than the Coulomb friction force, $\mathbf{F}_{\mathrm{t},ij}$, this term should be replaced by $\mathbf{F}_{\mathrm{t},ij}$. The parameters required to calculate the above forces are shown in Table 2 and are further discussed in Section Simulation conditions and procedure.

### *Governing equations for the gas phase*

We used *Fluent* commercial software (ANSYS, America) to describe the gas phase behavior and compiled the coupling code using *VS 2010* (Microsoft, America). The DEM–CFD coupling module was used to couple the DEM simulation with the CFD. The coupling module uses the existing Eulerian–Eulerian model in the CFD