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Simulation of particle flow in a bell-less type charging system of a blast furnace using the discrete element method

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ABSTRACT

A three-dimensional model was established by the discrete element method (DEM) to analyze the flow and segregation of particles in a charging process in detail. The simulation results of the burden falling trajectory obtained by the model were compared with the industrial charging measurements to validate the applicability of the model. The flow behavior of particles from the weighing hopper to the top layer of a blast furnace and the heaping behavior were analyzed using this model. A radial segregation index (RSI) was used to evaluate the extent of the size segregation in the charging process. In addition, the influence of the chute inclination angle on the size segregation and burden profile during the charging process was investigated.

1. Introduction

A blast furnace is a countercurrent reactor involving complex heat transfer, mass transfer, momentum transfer, and chemical reactions between ascending gas and descending solid materials. Optimizing the burden distribution is one of the most important factors for efficient operation of a blast furnace because the efficiency of smelting is dominated by the gas distribution, which is significantly affected by the burden distribution. A blast furnace is like a black box, and the phenomena inside are not directly observable for operators. With the development of a bell-less type charging system, the diversity and flexibility have been enhanced greatly. At the same time, the flow behavior of particles has become more complex. Hence, many studies have focused on the falling trajectory and distribution of the burden during the charging process (Jimenez et al., 1998; Nag & Koranne, 2009; Radhakrishnan & Ram, 2001; Wang, 2003, 2006; Yang et al., 1991). Empirical correlations (Du & Yu, 1986; Liang, Yu, Bai, Qiu, & Zhang, 2009) based on physical experiments have been developed for describing the burden movement. However, these empirical correlations lack universality. Assuming no interaction between particles, the equation of motion based on the classical mechanics theory of single particle was proposed to calculate the falling trajectories and impact points of burden (Nag & Koranne, 2009; Park, Jung, Jo, Oh, & Han, 2011; Qiu et al., 2011; Radhakrishnan & Ram, 2001; Yu et al., 2009). However, the materials used in a blast furnace consist of particles with diverse sizes, densities, shapes, and other mechanical properties, and they behave as discrete granular flow, which gives the computed results of the equation a large deviation when compared with the experimental data. In addition, it is difficult to understand the mechanisms of the formation of the burden profiles.

The flow behavior of a particle system depends on the collective interactions of the individual particles. To understand the flow behavior and segregation of the granular materials at the microscopic scale, as a feasible numerical approach, the discrete element method (DEM) originally developed by Cundall and Strack (1979) is applied in the present work. In recent years, DEM has been increasingly extended and used in simulating various solid flows. For instance, Zhou et al. (Zhou, Wright, Yang, Xu, & Yu, 1999; Zhou, Xu, Yu, & Zulli, 2001, 2002) investigated the angle of repose of coarse spheres in a rectangular container using DEM simulations and experimental studies. Cleary and Sawley (2002) studied industrial granular flows and the effect of particle shape on hopper discharge in a 3D case using the DEM. Ketterhagen, Curtis, Wassgren, and Hancock (2008, 2009) investigated granular segregation and flow modes in wedge-shaped and conical hoppers using DEM in which the flow from the hoppers could be divided into “mass flow” and “funnel flow”, and a relation between the

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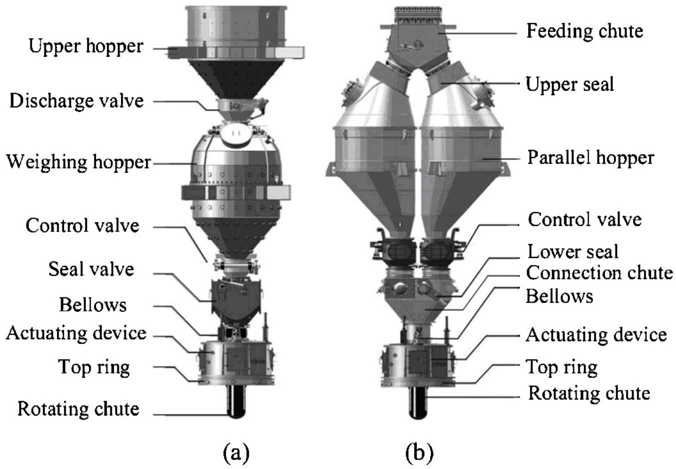

Fig. 1. Structure diagram of the bell-less top charging system: (a) serial-hopper type and (b) parallel-hopper type.

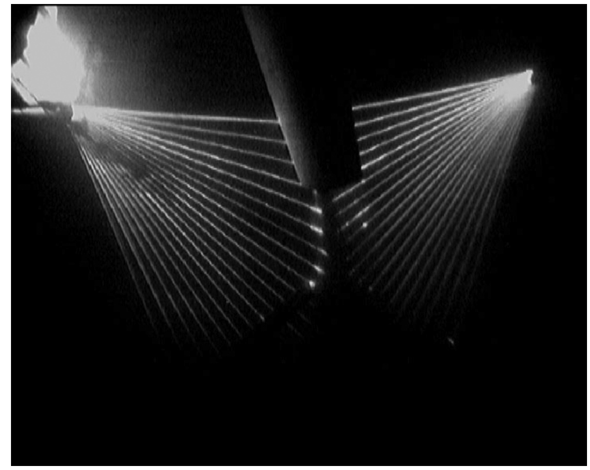

Fig. 2. Image of the laser grid cut by the burden stream.

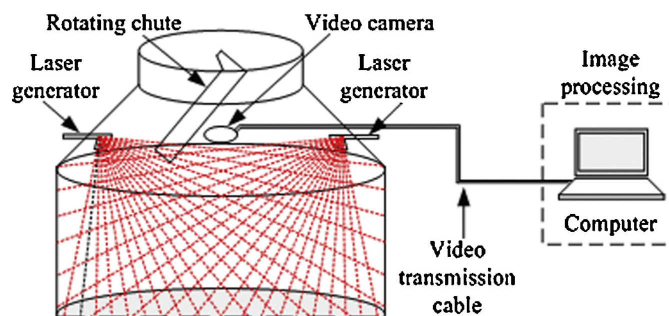

Fig. 3. Schematic diagram of the burden trajectory measurement by laser grid method.

macroscopic friction angle and the microscopic friction coefficient was proposed. Ho, Wu, Zhu, Yu, and Tsai (2009) investigated gouge formation mechanisms related to the burden distribution in blast furnaces by DEM simulations and physical experiments. Yu and Saxen (2010) studied the segregation of ternary size particles in a blast furnace top bunker model based on DEM, and discussed the factors of size segregation during the discharging process. Nouchi, Sato, Sato, Takeda, and Ariyama (2005) analyzed the stress field and solid flow of coke beds in blast furnaces using DEM. Natsui, Ueda, et al. (2011) and Natsui, Nogami, et al. (2011) analyzed the gas and solid flows in blast furnaces by hybrid models that coupled DEM and computational fluid dynamics. Mio et al. (2008, 2009, 2010) and Mio, Kadowaki, Matsuzaki, and Kunitomo (2012) developed DEM models to study the particle size segregation and charging behavior in bell-type and bell-less charging processes of blast furnaces, and a full model of a charging system simulator to analyze the segregation and flow behavior of particles in parallel-hopper type bell-less top blast furnaces. However, the layout of serial type hoppers is different from that of parallel type hoppers, as shown in Fig. 1. When discharged from serial type hoppers, the burden flows through the orifice at the center of the blast furnace, which makes the particle behavior unlike that in parallel hoppers (Kondoh et al., 1982). However, few papers have focused on the particle behavior and heap formation during the charging process for serial-hopper-type bell-less top blast furnaces, though it is very important for industrial production. Therefore, the charging behavior in serial-hopper-type bell-less top blast furnaces needs to be studied at the particle scale to control the burden distribution effectively and to achieve a rational gas flow pattern in the operation of blast furnaces.

In this study, a three-dimensional model was developed using DEM to simulate a serial-hopper-type bell-less charging system of a blast furnace with an inner volume of 3200 m^3. The flow behavior of particles in the charging system was analyzed by this model. The simulation results of the burden falling trajectory were compared with the industrial charging measurements based on the laser grid method (Gao & Dai, 2009) to validate the applicability of the simulation model. Furthermore, the influence of the chute inclination angle on the size segregation and burden profile during the charging process was investigated.

2. Experimental method

The burden falling trajectory measurements were conducted using the laser grid method (Gao & Dai, 2009; Gao, Liu, & Gao, 2010) at an actual blast furnace during the charging process for blow-in. As shown in Fig. 2, two laser generators, each transmitting 20 laser beams, were arranged in the chute manhole and lighting hole in the opposite directions. The laser grid, which is formed by the interweaving of the 40 laser beams, can serve as the frame of reference. A video camera was installed in the hole in a direction perpendicular to the plane of laser grid. Fig. 3 shows the measurement procedure of the burden trajectory using the laser grid method. As the chute rotates at an inclination angle, the burden stream cuts the laser grid and the image of the burden trajectory is captured by the video camera. The signals are transmitted to a computer by a video transmission cable, and processed by an image processing system (Gao, Zhao, Wu, Lin, & Gao, 2010). The burden trajectory data at different angles are then obtained.

Table 1
Components of the forces and torque acting on particle i.

Force and torque	Symbol	Equation
Normal contact force	$F_{cn,ij}$	$-k_n\delta_n^{3/2}\boldsymbol{n}$
Normal damping force	$F_{dn,ij}$	$-c_n\,\boldsymbol{u}_{n,ij}$
Tangential contact force	$F_{ct,ij}$	$-k_t\boldsymbol{\delta}_t$
Tangential damping force	$F_{dt,ij}$	$-c_t\,\boldsymbol{u}_{t,ij}$
Gravity		$m_i\,\boldsymbol{g}$
Torque	$T_{t,ij}$	$\boldsymbol{d}_i\times(\boldsymbol{F}_{ct,ij}+\boldsymbol{F}_{dt,ij})$
Rolling friction torque	$T_{r,ij}$	$-\mu_r\lvert\boldsymbol{F}_{cn,ij}+\boldsymbol{F}_{dn,ij}\rvert\hat{\boldsymbol{\omega}}_i$

where
$c_n=2\beta_n(m_{ij}k_n)^{1/2}$, $c_t=2\beta_t(m_{ij}k_t)^{1/2}$, $\boldsymbol{n}=\boldsymbol{d}_{ij}/\lvert\boldsymbol{d}_{ij}\rvert$, $\delta_n=R_i+R_j-\lvert\boldsymbol{d}_{ij}\rvert$,
$m_{ij}=m_im_j/(m_i+m_j)$, $\boldsymbol{u}_{ij}=\boldsymbol{u}_j-\boldsymbol{u}_i+\boldsymbol{\omega}_j\times\boldsymbol{d}_j-\boldsymbol{\omega}_i\times\boldsymbol{d}_i$, $\hat{\boldsymbol{\omega}}_i=\boldsymbol{\omega}_i/\lvert\boldsymbol{\omega}_i\rvert$,
$\boldsymbol{u}_{n,ij}=(\boldsymbol{u}_{ij}\cdot\boldsymbol{n})\,\boldsymbol{n}$, $\boldsymbol{u}_{t,ij}=\boldsymbol{u}_{ij}-\boldsymbol{u}_{n,ij}$.
Note that $\boldsymbol{F}_{ct,ij}+\boldsymbol{F}_{dt,ij}=-\mu_s\lvert\boldsymbol{F}_{cn,ij}+\boldsymbol{F}_{dn,ij}\rvert\boldsymbol{\delta}_t/\lvert\boldsymbol{\delta}_t\rvert$, provided $\lvert\boldsymbol{F}_{ct,ij}+\boldsymbol{F}_{dt,ij}\rvert>\mu_s\lvert\boldsymbol{F}_{cn,ij}+\boldsymbol{F}_{dn,ij}\rvert$.