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Segregation behavior of particles in a top hopper of a blast furnace

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ABSTRACT

The particle segregation in the hopper located above the bell-less top charging equipment is a factor that affects the radial size distribution in the blast furnace, and as the burden distribution determines the gas distribution it has implications for the whole furnace operation. The effect of four different particle shapes on the in-bin and discharge segregation of particles in the hopper was studied by the discrete element method. The calculated results were validated by comparing them with experimental results on coke segregation reported in the literature. It was found that the behavior of spherical particles showed the closest correspondence with the experimental results for large- and small-size coke segregation along the radial direction. The results of the study indicated that particle shapes have little effect on the simulated size segregation but, indeed, an effect on the continuity of the flow, and that spherical particles can be used to estimate the segregation of coke particles during hopper charging and discharging.

1. Introduction

The world-wide economic uncertainty, global competition and recent concern about global warming issues are huge challenges for the steelmaking industry, as expenses have to be cut and the carbon dioxide emissions have to be drastically reduced in the future. Therefore, it is important to further reduce the rate of reducing agent and to make full use of energy in the operation of the blast furnace. A prerequisite of this is that the heat exchange and chemical reactions between the reducing ascending gases and the descending solid burden be carried out properly in every region of the process. As the distribution of the solids in the lumpy zone controls the radial distribution of the bed permeability and lower down in the furnace the formation of the cohesive zone, the efficiency of the process can largely be controlled by optimizing the burden distribution. In pursue of this goal, the furnace should be charged in a way where the large and fine particles distribute appropriately on the burden surface. For instance, fine particles may be charged to the periphery to protect the lining or to prevent excessive heat losses, while large particles can be used to form a narrow region in the furnace center to facilitate a gas flow distribution with low pressure loss and smooth operation without disturbances in the burden descent. Size segregation of the burden materials prior to and at charging is known to be an important factor influencing the gas distribution. Therefore, size segregation of coke and sinter and flow patterns in filling and emptying of blast furnace hoppers have been investigated experimentally. Standish and Kilic [1,2], Kajiwara et al. [3] and Aminaga et al. [4], among others, studied the problem in small scale. Even though these investigators carried out many experiments, the information obtained from the investigations, e.g., on size segregation and flow patterns, is still limited. Therefore, more work is needed in order to understand size segregation of particles in the hopper and the general behavior as well as more detailed aspects of segregation of solid particles.

Since its original development by Cundall and Strack [5], the discrete element method (DEM) has gradually become a feasible numerical method for analyzing discontinuous media. The technique has already been extensively applied to simulate different granular flows in the industries, such as drum mixers [6], fluidized beds [7,8], vibrated beds [9,10], hopper charging and discharging flows [11–14], flow on inclined chutes [15–17] and conditions at blast furnace charging and burden descent [18–23].

Different kinds of hoppers have been studied, including cylindrical hoppers [24], bins [12], conical hoppers (silos) [25], and rectangular and wedge-shaped hoppers [26,27]. Li et al. [11] investigated numerically and experimentally pebble flow in a semi-cylindrical hopper with mono-size spheres and found good agreement between experimental and DEM results. Yu and Saxén [14] studied the outflow segregation of spherical particles from a small hopper by DEM, and compared the findings with small-scale experiments using mini-pellets. They found a good agreement between the predicted and the observed outflow patterns, demonstrating that the flow patterns in the hopper could be accurately captured by the numerical technique. Zhu et al. [24,28] analyzed unsteady and steady-state granular flows numerically in a 3D cylindrical hopper with a flat bottom. Ketterhagen et al. [27,29] modeled the material flow modes and size segregation during the discharging of wedge-shaped and conical hoppers by using DEM and proposed a relationship between a macroscopic friction angle and a microscopic friction coefficient. Chu [30] studied size segregation of

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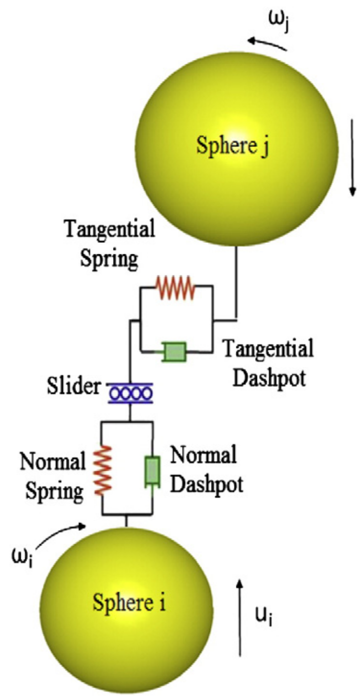

Fig. 1. Model of interaction forces between particles in DEM.

three different materials (glass bead, steel shot and crushed media) in the discharging process of an ASTM standard hopper, analyzed the effects of various particle treatments, the properties of particles and discharging methods and found that the extent of segregation for mixtures of crushed glass–crushed glass was similar to that of the spherical glass mixtures. Jin et al. [31], Höhner et al. [32], Tao et al. [33] and Langston et al. [34] focused on the behavior of non-spherical particle flow in hoppers with funnel flow type. Furthermore, Chung et al. [9, 10] proposed a novel technique to measure the velocity field of non-spherical particles and validated it by experimental results.

The above DEM and experimental investigations of the behavior of non-spherical particles in the charging and in the discharging process focused on hoppers of common types, and some of the work also considered size segregation of spherical particles in a Paul–Wurth (PW) hopper. However, despite the marked importance of PW-type hoppers in blast furnace charging systems, studies focusing specifically on size segregation during discharge in such hoppers are still scarce, with the exception of work reported in [35,36], and the material simulated in these studies was only spherical. For instance, Wu et al. [35] estimated the effect of the burden apex in the hopper and the slope of the lower part of the hopper on size segregation behavior of spherical particles during charging into and discharging from a PW-type hopper. Thus, the present paper contributes by computationally describing the segregation of non-spherical particles in a PW hopper, comparing the findings with experimental results reported in the literature.

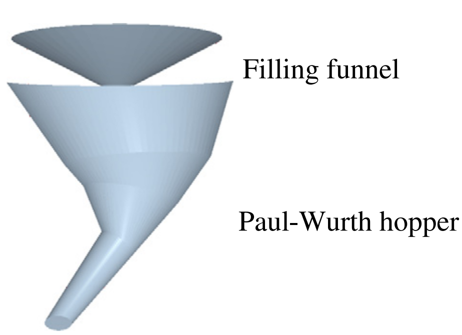

Fig. 2. Hopper and simulated filling method.

In this paper, DEM was applied to study the effect of non-spherical particle shapes on the size segregation of particles in a scaled model PW hopper of the type experimentally studied by Standish [1]. Section 2 introduces the simulation method, procedure and the model parameters. In Section 3, the system studied and the simulation procedure for the hopper charging and discharging processes are presented, as well as the way in which the irregular particles have been modeled. Section 4 presents results of the simulated size segregation and compares them with experimental findings reported in the literature. This section also presents some more detailed analysis from the DEM simulations concerning the motion of the particles. Finally, conclusions are drawn and future extension of the work is proposed.

2. Discrete element method

The motion of particles, both translational and rotational, can be described by Newton's second law of motion combined with a force–displacement correlation at the points of contact between the particles. In the discrete element method (DEM) [5], the particle contact model (Fig. 1) is represented by a spring and a dashpot, representing the elastic and plastic nature of particles in the normal direction. In the tangential direction, the model represents a frictional slider, a spring and a dashpot. For a particle, i, the governing equations in interaction with another particle, j, are [15,21]

$$m_i \frac{du_i}{dt} = \sum_{j=1}^{n} \left(F_{cn,ij} + F_{dn,ij} + F_{ct,ij} + F_{dt,ij} \right) + G_i \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n} \left(T_{t,ij} + T_{r,ij} \right) \quad (2)$$

where u_i, I_i and ω_i are the translational velocity, moment of inertia and angular velocity, respectively. The forces are the gravitational

Table 1
DEM parameters used in the simulation. Steel plane and plexiglass properties are from the material database of the EDEM software, while the diameters of particles used in the simulation are the intermediate values of the intervals of the real particle diameters.

Parameter	Value
Particles	
Total number of particles	147,266
Mass ratio of particles m_1:m_2:m_3	1:1:1
Diameter of small particles, d_1 (mm)*	1.5
Number of small particles	141,229
Diameter of intermediate particles, d_2 (mm)*	4.5
Number of intermediate particles	5144
Diameter of large particles, d_3 (mm)*	7.08
Number of large particles	893
Density (kg/m^3)	1000
Shear modulus (GPa)	1
Poisson's ratio	0.25
Interparticle static friction coefficient	0.5
Interparticle rolling friction coefficient	0.2
Interparticle restitution coefficient	0.45
Steel plane	
Poisson's ratio	0.30
Shear modulus (GPa)	7.0
Density (kg/m^3)	7800
Particle-plane static friction coefficient	0.5
Particle-plane static friction coefficient	0.1
Particle-plane restitution coefficient	0.35
Plexiglass properties	
Poisson's ratio	0.4
Shear modulus (GPa)	0.1
Density (kg/m^3)	1500
Particle-hopper static friction coefficient	0.5
Particle-plane rolling friction coefficient	0.02
Particle-hopper restitution coefficient	0.2
Time step (s)	4×10^{-5}