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Quantitative comparison of binary particle mass and size segregation between serial and parallel type hoppers of blast furnace bell-less top charging system

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ABSTRACT

Uniform particle packed-bed permeability facilitates a smoother operation and a higher energy efficiency of the blast furnace ironmaking process. Two types of bell-less top charging systems, namely, serial and parallel type hoppers, are widely applied in practical production to distribute the burden particles into the furnace throat. The emergence of particle segregation behaviors directly influences permeability in radial and circumferential directions. In this work, after mapping 40 blocks with equal areas in the furnace throat, quantitative methods are proposed to characterize and compare mass and size segregation behaviors when binary-sized particles are charged from serial and parallel type hoppers. Based on the results obtained from discrete element method simulation, the average particle velocity in the horizontal x–y plane at the exit of the rotating chute under the serial type hopper is approximately 0.3 m/s greater than that under the parallel type hopper, which causes the difference in mass segregation in the radial direction. Furthermore, the velocity in the z-axial direction demonstrates a cosine-like curve under the parallel type hopper during the entire discharge process, which results in its mass segregation in the circumferential direction. The particle flow on the rotating chute concentrates with a narrower width under the serial type hopper, so, the small particles aggregate in the smaller central area. By contrast, the wider particle flow width under the parallel type hopper helps distribute the small particles into the larger central area. Moreover, the effect of particle size and chute inclining angle on the difference in the above segregation behaviors between the serial and parallel type hoppers are further investigated.

1. Introduction

Particle segregation is an inevitable phenomenon during the processes of mixing, conveying, filling, discharging, and compaction. Due to the difference in particle characteristics, particle segregation is existed in terms of mass, size, density segregations in various industries, such as drum mixers [1–2] fluidized beds [3–4], vibrated beds [5–6], blast furnace [7–8] and others [9–12]. Taking the blast furnace process for example, particle mass and size segregation in the furnace shaft leads to poor and uneven bed permeability, the resulting lower heat exchange efficiency between the ascending gas and descending particles restrains the reduction rates of iron oxides, as well as hot metal productivity. Therefore, controlling particle segregation to obtain a desired gas flow and smooth operation for the blast furnace process is of critical importance.

There are two different blast furnace bell-less top charging systems, namely serial type hopper and parallel type hopper, widely used to discharge particles into the furnace throat in the practical production. For serial type hopper, in addition to particle falling trajectories and distribution profiles [13–16], the effects of parameters on particle size segregation are studied when the particles flowed out of the hopper. Ketterhagen [17] and Yu [18] addressed particle rolling friction and filling method made an important influence on the size distribution, whereas the effect of particle shape could be neglected [19–20]. What's more, the size segregation could be reduced by optimizing the position of hopper outlets [21]. For parallel type hopper, both theoretical analysis [22–25] and experimental measurement [26–27] were employed to clarify the segregation behaviors. The uneven mass distribution in the circumferential direction was characterized by Liu [22], Ren and Xu [23–24], and the contradictory conclusions were made concerning the location of the region with maximum mass. To be specifically, Liu stated that the region with the maximum mass was located at 180° while the other two clarified at 90°. Size segregation involved in either the charging or discharging processes was also investigated [28–29] as that in the case of serial type hopper, and most segregation index were proposed based on mass fractions of different size particles or related mass fraction ratios [16, 26, 30–31].

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Nomenclature

m_i	mass of particle i
$\mathbf{u_i}$	translational velocity of particle i
t	time
K	number of particles in contact with particle i
$\mathbf{F_{cn,ij}}$	normal contact force between particle i and particle j
$\mathbf{F_{dn,ij}}$	normal damping force between particle i and particle j
$\mathbf{F_{ct,ij}}$	tangential contact force between particle i and particle j
$\mathbf{F_{dt,ij}}$	tangential damping force between particle i and particle j
$\mathbf{g}$	gravitational acceleration
$\mathbf{I_i}$	moment of inertia of particle i
$\mathbf{T_{t,ij}}$	tangential torque acting on particle i
m	meter or mass
mm	millimeter
SI	segregation index
X_f	the mass fraction of smaller particles in each block
X_i	the initial mass fraction of smaller particles
IMF	the initial mass fraction of smaller particles

Greek alphabets

$\boldsymbol{\omega_i}$	angular velocity of particle i
ρ	bulk density of the material
α	chute inclining angle with respect to the center line

Subscripts

i	particle i or initial
j	particle j
n	normal direction
t	tangential direction
c	contact force
d	damping force

Although a lot of work concerning particle segregation on blast furnace bell-less top has been reported, only few investigations have been conducted to compare the radial and circumferential mass and size segregation in the furnace throat systematically and quantitatively between serial and parallel type hoppers. In this work, two 3D mathematical models of serial and parallel type hoppers are established based on DEM after the parameters are validated against the experimental measurements. The binary-sized particles are discharged from the hoppers, and mass and size segregation behaviors in the furnace throat are quantitatively characterized based on the proposed visualized method. The comparison and difference in the segregation between the two types of hoppers are explained. Furthermore, the effects of particle size and chute inclining angle on the results are investigated.

2. Numerical and analytical methods

2.1. DEM simulation model

With the development of computational methods and technology, the discrete element method (DEM), which was developed by Cundall and Strack [32], has become one of the most well-known and powerful simulation methods for analyzing particle segregation and has already been extensively applied in various fields. Zhu et al. [33] systematically and comprehensively reviewed the DEM simulation and concluded that it was an effective and reliable method to investigate particulate matter. Moving particles in a granular system collide with neighboring particles or wall, the involved forces in the DEM, are determined by Newton's second law of motion. Fig.1 illustrates the inter-particle contact model, including the spring and dashpot in the normal direction and spring, dashpot, and slider in the tangential direction. The governing equations for the interactions between particles i and j can be expressed as

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

$$\mathbf{I_i} \frac{d\boldsymbol{\omega_i}}{dt} = \sum_{j=1}^{K} \mathbf{T_{t,ij}} \quad (2)$$

where m_i, $\mathbf{I_i}$, $\mathbf{u_i}$, and $\boldsymbol{\omega_i}$ represents the mass, moments of inertial, translational velocity, and angular velocity of particle i, respectively. In addition to the gravitational force ($m_i\mathbf{g}$), the inter-particle forces affecting particle i are summed over K particles. There are two components: one arises from the normal and tangential contact/damping forces, $\mathbf{F_{cn,ij}}$ and $\mathbf{F_{ct,ij}}$/$\mathbf{F_{dn,ij}}$ and $\mathbf{F_{dt,ij}}$, respectively and the other is the torques $\mathbf{T_{t,ij}}$, exerted by the tangential forces.

2.2. Model dimensions and simulation parameters

Two schemes of 3D bell-less top burden charging hopper models of blast furnace, namely, serial and parallel type hopper models, are established to investigate the difference in particle mass and size segregation during the discharging process. The geometric dimensions and bird's-eye views of these two hopper models are shown in Fig. 2. Specifically, #1 hopper is placed in the center of the serial type hopper model. By contrast, #1 and #2 hoppers are placed in the direction of 90°and 270° of the parallel type hopper model. In addition, the models' bottoms are flat, so the particles are assumed to fall on a horizontal burden surface. In the following DEM simulation work, only #1 hopper of each model works for discharging particles and both chutes rotate counterclockwise after reaching a certain inclination angle α.

As analyzed in the authors' previous work [24], the location of hoppers inevitably affects the particle trajectory. In the serial type hopper, the falling particles directly reach the rotating chute along the center line and the colliding point on the rotating chute is almost fixed during

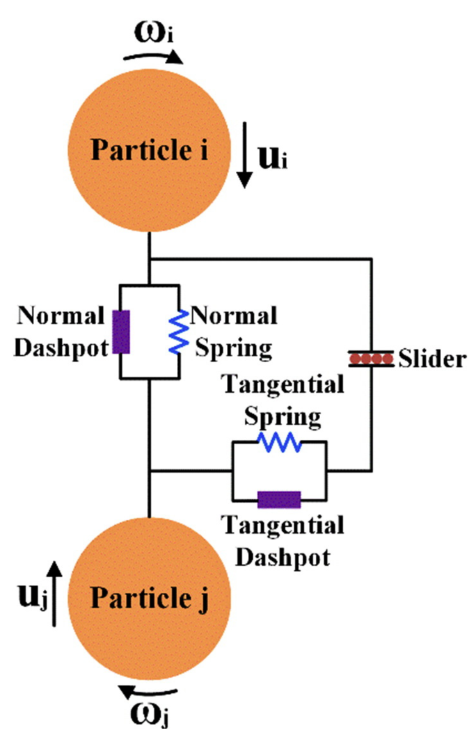

Fig. 1. Schematic of the interaction between particles i and j in the DEM simulation.