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Transient local segregation grids of binary size particles discharged from a wedge-shaped hopper

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A B S T R A C T

This work presents a novel method to quantitatively characterize and investigate the transient local segregation behavior of the binary (3 and 6 mm) particles inside a wedge-shaped hopper during the discharge process. The space in which binary particles existed is first mapped by the 10 mm × 10 mm square grids. Based on the data obtained by discrete element method (DEM) simulation, the ratios of the transient mass fraction of 3 mm particles in the mixture to the original fraction are calculated and then clarified into the seriously positive (++), positive (+), well-mixed (0), negative (−), and seriously negative (−−) levels, respectively. The relationships between the fraction of each segregation index (SI for short) and the flowing time are quantitatively analyzed in the center, middle, and edge regions. The local segregation begins to change when the flowing time reaches 1000 ms, which is about half of the total discharge time. Along with the formation of a 'V' shape funnel flow, the large-sized particles prefer to roll toward the center of the hopper, thereby leading to negative segregation, and both the fractions of SI(−) and SI(−−) increase by as high as 0.6 and 0.3, respectively. Under the present simulation conditions, the factors of the initial mass ratio of the large size particle to the small one, and the particle density, directly and obviously affect the transient local segregation behavior, and the fraction of SI(−−) in the center region is increased by at least 0.4. The particle size difference mainly affects the segregation behavior in the edge region at a limited degree, specifically when the particle size difference increases by 1 mm, the fraction of SI(0), which is used to determine the uniform degree of the mixture, is reduced by about 0.1. In addition, the influences of both the friction coefficient among the particles and that between the particles and the wall on the segregation behavior during the discharge process can be negligible in comparison with other factors.

1. Introduction

The segregation behaviors of the granular materials, composed of different sizes, densities or shapes particles, have been a prevalent but typically undesirable phenomena in the industrial processes. Taking the blast furnace ironmaking process as an example, due to the particle size segregation, the poor permeability in the radial direction directly affects the heat transfer efficiency between the gas and the solid, thus correspondingly decreasing the chemical reaction rates in the practical production. It is of great importance to understand and characterize the particle segregation behaviors before the strategies are taken.

Previous work indicated that the granular material properties, the device geometry and the operation parameters, made a direct and important effect on the particle segregation behaviors [1]. Both Standish [2] and Shinohara [3] found that the particles of different size begins to segregate in the initial discharge process. The particle shape made little effect on the above mentioned behaviors, but the smooth flow was more easily to be blocked when the shape became more complicated from sphere to triangle, cylinder, and even hexahedron [4]. The effects of other particle properties, such as density, diameter ratio, mass fraction in the mixture, on the segregation were also studied [5–7], and the denser particles were found to tend to concentrate close to the central feed point. Meanwhile, Mio [8], Shinohara [9–10] and Abatzoglou [11] focused on the influences of the hopper filling or discharging rate, as well as the device geometry on the particle segregation behaviors. All in all, lots of previous work [12–14] concluded that the particle size in comparison with other properties is the dominant factors concerning the segregation phenomena during the discharge process.

As far as the characterization of the particle size segregation was concerned, Jullien and Meakin [15] counted the particle number in either vertical or horizontal direction to evaluate the segregation degree. Shinohara [16] employed the deviation ratio of the particle's concentration to its initial distribution at the different locations to assess the uneven distribution. Meanwhile, a ternary size diagram was proposed by

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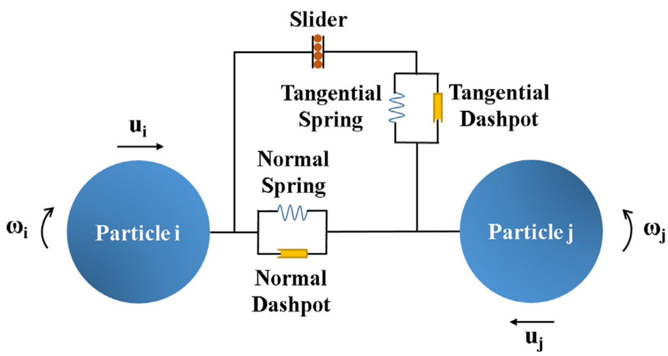

Fig. 1. Schematic illustration of the interaction between particles i and j in the DEM simulation.

Shimokawa [17] to characterize the particle size segregation in the packed sandpile. In addition, there were some other characterization methods concerning the size segregation behaviors summarized in these works [4,18–22].

Although the particle segregation behaviors were widely studied by the previous works, few focus on the local segregation and its transient features during the discharging process. In the present work, by employing discrete element method (DEM) simulation, the 3 mm and 6 mm diameters particles under equal mass ratio are firstly mixed and charged into the wedged-shape hopper, and then the bottom outlet is opened to discharge the binary size particles out of the hopper. The ratio of transient mass fraction of the 3 mm diameter particles to the original fraction in each established grid is calculated, and further clarified into five different segregation levels, namely seriously positive level, positive level, well-mixed level, negative level, and seriously negative level respectively. As a result, the relationships between the particle local segregation behaviors and the flowing time during the discharging process are quantified analyzed. The proposed method is also applied to discussed the effects of mass ratio, particle diameter, density, as well as frictional coefficient, on the transient segregation behaviors.

Table 1
Parameters used in the DEM simulation (The parameters with underline are used for base case study).

Parameters	Value
Diameter of particles, D_p(mm)	$\underline{3}$, 5, 6, 7
Density of particles of particles, ρ_p (kg/m^3)	1050, $\underline{2100}$, 4200
Mass fraction of smaller size particles in the mixture, X_f (−)	0.3, $\underline{0.5}$, 0.7
Young's modulus of particles, G_p (GPa)	375
Poisson's ratio of particles, υ_p (−)	0.22
Coeff. of interparticle friction, $\mu_{p\text{-}p}$ (−)	0.2, $\underline{0.5}$, 0.8
Coeff. of interparticle restitution, $e_{p\text{-}p}$ (−)	0.6
Coeff. of wall-particle friction, $\mu_{w\text{-}p}$ (−)	0.1, $\underline{0.4}$, 0.7
Coeff. of wall-particle restitution, $e_{w\text{-}p}$ (−)	0.7
Time step (s)	1×10^{-4}

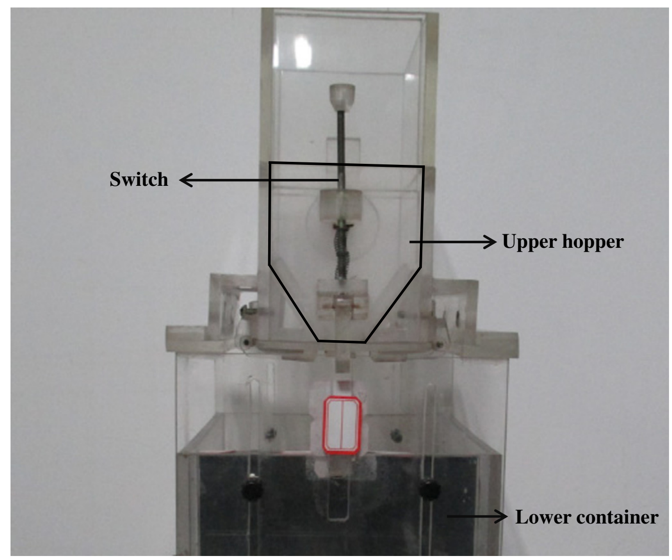

Fig. 3. Wedged-shape hopper (Upper hopper) used in the physical experiment with the same geometric dimension indicated in Fig.2.

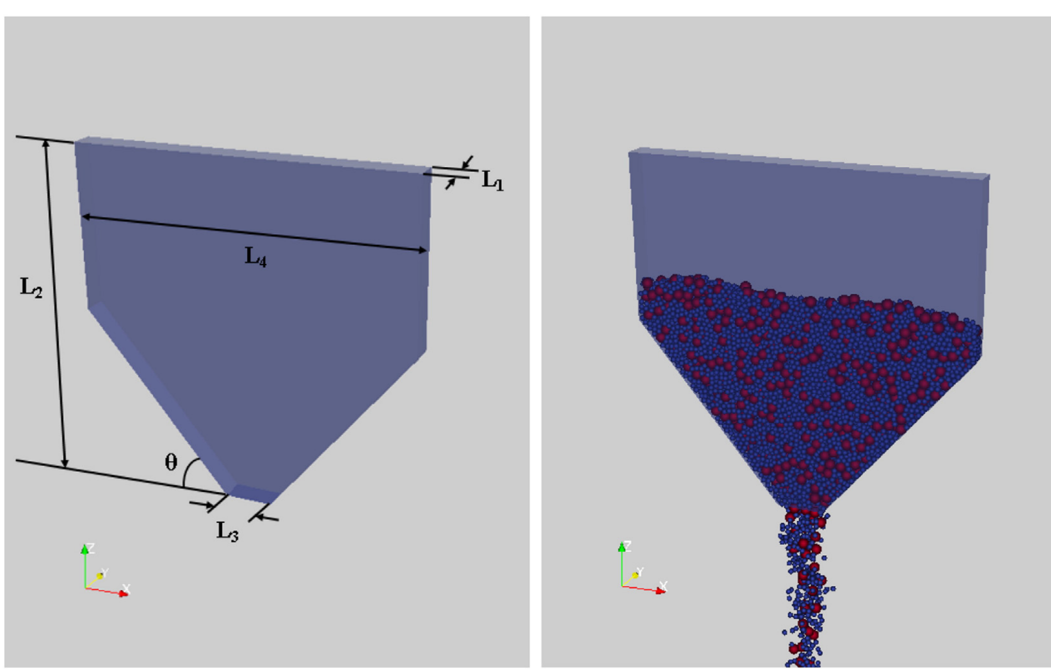

Fig. 2. Geometry of the wedged-shape hopper used in the numerical simulation. $L_1 = 14$ mm, $L_2 = 220$ mm, $L_3 = 28$ mm, $L_4 = 200$ mm, $\theta = 50°$.