Local Percolation of a Binary Particle Mixture in a Rectangular Hopper with Inclined Bottom during Discharging

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ABSTRACT: To reveal the local percolation characteristics of a binary particle mixture in a rectangular hopper with inclined bottom, the discrete element method (DEM) is used to simulate the discharging process. A local percolation evaluation method is proposed, and the percolation strength grid maps are drawn. The effects of geometric parameters, particle properties, and interaction parameters on percolation are investigated. Apart from the free surface, percolation is mainly concentrated near the wall and at the bottom. With the increase in the orifice width, the average local percolation strength index (ALPSI) of the near-wall region increases and that of the bottom region decreases. The effect of the angle on percolation in the near-wall region can be ignored. The effect of friction on local percolation is significant. Increasing the fine particle mass fraction and reducing the difference in particle size can effectively avoid percolation.

1. INTRODUCTION

Segregation is regarded as the opposite of mixing, which results in the partial or total separation of well-mixed particle components. Segregation often occurs in the processing of particulate materials due to their different properties.1–3 Although segregation is important in the beneficiation industry, it is usually undesirable or even problematic because the product is usually required to maintain a certain mixing uniformity. For example, in the iron-making industry, segregation leads to uneven distribution of particle mixture, which further affects the permeability of the bed and greatly reduces the reaction efficiency and heat transfer efficiency. In addition, in the pharmaceutical industry, segregation leads to changes in drug concentrations, and batches with incorrect potency may be re-called. The main mechanism of segregation is percolation.4–6 Therefore, it is necessary to fundamentally discuss the physical mechanism of segregation, which is beneficial to deepen the understanding of transport and mixing of multiscale particles in industry.

In the past, some research studies on particle percolation have been conducted. For example, percolation of spherical particles,7 cohesive particles,8 and nonspherical particles9 in packed beds has been extensively studied. In addition, percolation in blast furnace burden10 and steady shear packed beds has been extensively studied. In addition, percolation in a hopper during discharging was also investigated. These are helpful in understanding percolation. However, with different operating conditions, percolation will be quite different. One example is percolation in a hopper during discharging.

As a kind of particulate material processing device, hoppers are widely used in chemical, metallurgical, pharmaceutical, and construction industries.12–14 In industry, most particulate materials are discharged from hoppers. The structure of a hopper is simple, but the flow behavior of the particles inside is very complicated, which is very interesting. In the past few decades, segregation of particles in hoppers has attracted great attention from scholars.15,16 Scholars have done a lot of research work on particle size segregation in hoppers by experiments and the discrete element method (DEM).17–24 Geometric parameters,25–27 particle properties,28–33 and interaction parameters34 have significant effects on segregation, and there is obvious percolation on the free surface.35 Among them, DEM, as an effective method, has been widely used in the simulation of particle motion.36–42 Some information that cannot be directly obtained in experiment can be obtained through DEM simulations.

It is worth mentioning that in recent years, the continuum segregation model has also made great progress.43–46 For example, in a recent study, a quantitative model was established, segregation in a hopper was successfully predicted, and percolation on the free surface was well reproduced.37 From the work given above, it can be seen that, apart from the free surface, percolation at other locations in a hopper during discharging is still unclear. In this work, percolation of a...
binary particle mixture in a rectangular hopper with inclined bottom is taken as the research object and DEM software EDEM 2018 (DEM Solution Ltd., Edinburgh, U.K.) is used to simulate the discharging process. To clarify the location and local strength of percolation, a local percolation strength index (LPSI) is proposed, and the percolation strength grid maps are drawn. The average local percolation strength index (ALPSI) of the percolation concentration region is calculated. The effects of geometric parameters, particle properties, and interaction parameters on percolation are investigated. This has important theoretical reference value for further understanding segregation during discharging and proposing control strategies.

2. SIMULATION METHODS

The DEM contact model is divided into two types according to the contact method: the hard sphere model and the soft sphere model.48 A large number of studies have shown that the soft sphere model is suitable for simulation of dense particle friction device. Newton abstracted as the joint action of a spring, damper, and sliding friction device. Newton’s second law is used to describe the motion of particles. Each particle in the system contains two modes of motion: translational motion and rotational motion. The calculations of translational motion and rotational motion are shown in eqs 1 and 2. The calculation equations of force and torque appearing in these equations are shown in Table 1.

\[
m \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{k} F_{ij}
\]

\[
I_i \frac{d\omega}{dt} = \sum_{j=1}^{k} T_{ij}
\]

where \(m_i\) is the mass of particle \(i\), \(\nu_i\) is the translational velocity of particle \(i\), \(g\) is the acceleration of gravity, \(k_i\) is the number of particles in contact with particle \(i\), \(F_{ij}\) is the contact force, \(I_i\) is the moment of inertia, \(\omega_i\) is the rotational velocity of particle \(i\), and \(T_{ij}\) is the torque.

| force and torque | equation | condition |
|------------------|----------|-----------|
| normal force, \(F_{nxj}\) | \(F_{nxj} + F_{dxj}\) |          |
| normal elastic force, \(F_{naj}\) | \(-4/3E_i\sqrt{\beta_i} \xi \sqrt{\beta_i} \xi\) |          |
| normal damping force, \(F_{naj}\) | \(-2\sqrt{j} \beta_i m_i \sqrt{\beta_i} \xi \sqrt{\beta_i} \xi\) |          |
| tangential force, \(F_{tij}\) | \(F_{tij} + F_{rij}\) | \(|F_{tij}| \leq |F_{rij}|\) |
| tangential elastic force, \(F_{tij}\) | \(-\beta_i m_i \sqrt{\beta_i} \xi \sqrt{\beta_i} \xi\) |          |
| tangential damping force, \(F_{tij}\) | \(-8G_{ij} \sqrt{\beta_i} \xi \sqrt{\beta_i} \xi\) |          |
| torque by tangential force, \(T_{tij}\) | \(r \delta_i \times F_{tij}\) |          |
| rolling friction torque, \(T_{rij}\) | \(-|F_{rij}| / \beta_i\) |          |

Table 1. Force and Torque Equations

3. VALIDATION

In the experiment, the cross-sectional area of the hopper is 180 mm × 36 mm, the height is 400 mm, the orifice area is 36 mm × 36 mm, and the angle between the bottom and the vertical direction is 45°. The experimental setup is shown in Figure 1. The orifice is closed before filling. Acrylic spheres with diameters of 6 and 2 mm are used as the experimental material. The fine particle mass fraction is 15%. The evenly mixed material is added into the hopper from the top, and the filling height is 400 mm. After the filling is completed, the orifice is opened and the particles are discharged from the hopper under the action of gravity. To validate the applicability of DEM, the experimental and simulated snapshots are compared (Figure 2). Furthermore, the cumulative mass discharge rates of fine particles are also compared (Figure 3). In the experiment, the sample is sampled by the discontinuous method,26 after which the sample is screened to determine the cumulative mass discharge of fine particles.

To ensure the accuracy of the validation results, in the validation simulation, the hopper size and particle properties are equivalent to the parameters in the experiment. The parameter settings are shown in Table 2. These values are obtained from experimental measurements, and details can be found in our previous work.56 They will also serve as the basis for subsequent calculations.

As can be seen from Figure 2, the flow pattern of the medium in the simulation is consistent with that in the experiment. In Figure 3, the cumulative mass discharge of fine particles is plotted as a function of the total mass discharge fraction. As can be seen from Figures 2 and 3, simulated results are in good agreement with experimental results. This shows that it is feasible to use DEM to simulate the percolation of a binary particle mixture in the hopper during discharging.
4. PERCOLATION EVALUATION METHOD

Percolation is the process of fine particles passing through the gaps between coarse particles. There is a velocity difference between coarse and fine particles when percolation occurs. Generally, the mass fraction of percolated particles, mean percolation velocity, diffusion velocity, and radial dispersion are used for percolation evaluation. 6–11 In recent years, segregation velocity and segregation flux have been proposed and used to construct continuum segregation models. 15–47 The above methods are fit for use for percolation and segregation. However, for the local percolation in a hopper during discharging, the local velocity difference is more suitable. It can directly reflect the local percolation in the hopper during discharging. In the current work, 10 mm × 10 mm grids are used to divide the area below 200 mm of the hopper, as shown in Figure 4. It should be noted that the selection of the grid size should be appropriate. It should not be too fine to ensure that the coarse particles are covered and that each grid contains a sufficient number of coarse and fine particles simultaneously. In addition, it should not be too coarse to avoid losing details of local percolation. In the current work, 10 mm × 10 mm grids are recommended by comparing the effects of three grid sizes (6 mm × 6 mm, 10 mm × 10 mm, and 14 mm × 14 mm) on the results.

\[
LPSI = \frac{V_f - V_c}{\sqrt{gd_c}}
\]

\[
V_f = \frac{\sum_{i=1}^{S} \sum_{j=1}^{N_{fi}} V_{fi}}{\sum_{i=1}^{S} n_{fi}}
\]

\[
V_c = \frac{\sum_{i=1}^{S} \sum_{j=1}^{N_{ci}} V_{ci}}{\sum_{i=1}^{S} n_{ci}}
\]

where \(V_f\) and \(V_c\) are the average velocities of fine and coarse particles in the grid, respectively, when the direction of gravity is positive; \(S\) is the number of sampling time points, which is related to the time step, which is 0.01 s here; \(n_{fi}\) and \(n_{ci}\) are the number of fine and coarse particles in the grid at the sampling time point \(t\), respectively; \(V_{fi}\) and \(V_{ci}\) are the velocities of fine particle \(i\) and coarse particle \(i\) in the grid at the sampling time point \(t\), respectively.

The velocity difference between coarse and fine particles in each grid is used to evaluate the local percolation strength. To avoid the fluctuation of instantaneous velocity, the average

Table 2. Parameter Settings

| type           | parameters     | value                        |
|----------------|----------------|------------------------------|
| particle       | diameter, \(d_c\) and \(d_f\) (mm) | 6, 2                         |
|                | fine particle mass fraction, \(M_f\) (%) | 15                           |
|                | Poisson ratio, \(\lambda_p\)           | 0.35                         |
|                | density, \(\rho_p\) (kg/m\(^3\))       | 1191                         |
|                | shear modulus, \(G_p\) (Pa)            | \(1.148 \times 10^8\)       |
| hopper         | orifice width, \(W_o\) (mm)            | 36                           |
|                | angle, \(\theta\) (°)                  | 45                           |
|                | Poisson ratio, \(\lambda_w\)           | 0.34                         |
|                | density, \(\rho_w\) (kg/m\(^3\))       | 1149                         |
|                | shear modulus, \(G_w\) (Pa)            | \(6.94 \times 10^8\)        |
| particle–particle | restitution coefficient, \(\tau_{ep}\) | 0.45                         |
|                | static friction coefficient, \(f_{s, ep}\) | 0.55                        |
|                | rolling friction coefficient, \(f_{r, ep}\) | 0.015                       |
| particle–wall  | restitution coefficient, \(\tau_{ww}\) | 0.84                         |
|                | static friction coefficient, \(f_{s, wp}\) | 0.45                        |
|                | rolling friction coefficient, \(f_{r, wp}\) | 0.01                        |

Figure 2. Comparison between experimental (top) and simulated (bottom) snapshots.

Figure 3. Comparison between experimental (point) and simulated (line) results.

Figure 4. Grid division of the hopper.
velocity when the medium surface drops from 390 to 250 mm is used for calculation. The acceleration of gravity \((g)\) and the diameter of the coarse particle \((d_c)\) are used to nondimensionalize the velocity difference. The local percolation strength index (LPSI) is calculated as shown in eq 3. To facilitate visualization, the grids are dyed according to the LPSI from large to small: red−yellow−white−blue.

5. RESULTS AND DISCUSSION

5.1. Orifice Width. Figure 5 shows the effect of different orifice widths on the LPSI. The orifice width is increased from 30 to 42 mm, with an interval of 3 mm. It can be seen from Figure 5 that the yellow and red grids are mainly concentrated near the wall and at the bottom of the hopper. This indicates that the percolation of the binary particle mixture in the hopper mainly occurs near the wall and at the bottom. This is related to the shear zone\(^{57}\) and the funnel flow.\(^{58}\) The shear zone is formed near the wall, and the funnel flow occurs at the bottom of the hopper. Fine particles pass through the gaps between coarse particles and percolation occurs. In other words, the relative motion between coarse particles is the key mechanism of percolation. In the following discussion, unless otherwise specified, all statements about velocity are for coarse particles.

In Figure 5, the number of dark yellow and red grids near the wall increases with orifice width. This shows that the probability of strong percolation near the wall increases. This is because, with the increase in orifice width, the stream velocity increases, the velocity gradient near the wall increases, and the percolation increases. The effect of different orifice widths on velocity distribution in the vertical section is shown in Figure 6a. With the increase in orifice width, the colors of red and dark yellow grids at the bottom become lighter and the distribution range of the dark yellow grid becomes wider. This shows that the percolation at the bottom is not only related to the velocity gradient but also to stream velocity. With the increase in orifice width, the stream velocity increases and the percolation is no longer significant. Moreover, the range of large velocity gradient becomes wider, so the distribution range of the dark yellow grids becomes wider. The effect of different orifice widths on velocity distribution at the bottom is shown in Figure 6b. It can also be seen from Figure 5 that there are blue grids at the orifice. This is related to the formation of the arch,\(^{59}\) and the percolation is hindered. The blue grid near the

![Figure 5](image-url)  
**Figure 5.** Effect of different orifice widths on the LPSI: (a) 30 mm, (b) 33 mm, (c) 36 mm, (d) 39 mm, and (e) 42 mm.

![Figure 6](image-url)  
**Figure 6.** Effect of different orifice widths on velocity distribution: (a) vertical section and (b) bottom.

![Figure 7](image-url)  
**Figure 7.** Effect of different orifice widths on the ALPSI.
bottom wall is due to the accumulation of fine particles whose movement is hindered by coarse particles.

\[
ALPSI = \frac{1}{N} \sum_{i=1}^{N} LPSI
\]

where \(N\) is the number of effective grids.

From the above analysis, it can be seen that the percolation of the binary particle mixture in the hopper is mainly concentrated near the wall and at the bottom of the hopper. To quantitatively analyze the local percolation characteristics, the average local percolation strength index (ALPSI) of the near-wall region and the bottom region is calculated. The near-wall region and the bottom region are defined based on the experimental parameters and the particle properties.

Figure 8. Effect of different angles on the LPSI: (a) 25°, (b) 35°, (c) 45°, (d) 55°, and (e) 65°.

Figure 9. Effect of different angles on velocity distribution: (a) vertical section and (b) bottom.

Figure 10. Effect of different angles on the ALPSI.

Figure 11. Effect of different friction coefficients between particles on the LPSI: (a) 0.15, (b) 0.35, (c) 0.55, (d) 0.75, and (e) 0.95.
wall region and the bottom region are shown in Figure 4. The calculation of the ALPSI is shown in eq 6. Note that a grid with particle coverage greater than half of the grid area is considered an effective grid. Figure 7 shows the effect of different orifice widths on the ALPSI. As can be seen from Figure 7, with the increase in orifice width, the ALPSI of the near-wall region increases, while that of the bottom region decreases. When the orifice width increases from 30 to 42 mm, the ALPSI of the near-wall region increases from 0.036 to 0.046 and that of the bottom region decreases from 0.047 to 0.030.

5.2. Angle. Figure 8 shows the effect of different angles on the LPSI. The hopper angle is increased from 25 to 65°, with an interval of 10°. It can be seen from Figure 8 that with the increase in the angle, the number of dark yellow and red grids near the wall decreases slightly. This shows that the probability of strong percolation near the wall decreases. This is because, with the increase in the angle, stream velocity decreases, and the velocity gradient near the wall decreases slightly. The effect of different angles on velocity distribution in the vertical section is shown in Figure 9a. With the increase of the angle, the colors of dark yellow grids at the center of the bottom deepen, the number of red grid increases, and the other positions become lighter. This is because, with the increase in the angle, the velocity gradient at the center of the bottom increases and the range of the large velocity gradient converges to the center. The effect of different angles on velocity distribution at the bottom is shown in Figure 9b. The percolation at the bottom is qualitatively consistent with segregation observed by Zhang et al.33

Figure 10 shows the effect of different angles on the ALPSI. It can be seen from Figure 10 that the ALPSI of the near-wall region is not sensitive to the angle. Although decreasing the angle and increasing the orifice size can both increase the velocity gradient near the wall, the orifice size plays a dominant role in the current work. This can be found in Figures 6a and 9a. This is why the ALPSI of the near-wall region is sensitive to the orifice width but not to the angle. The ALPSI of the bottom region decreases with the angle. When the angle increases from 25 to 65°, the ALPSI decreases from 0.044 to 0.024.

5.3. Friction between Particles. Figure 11 shows the effect of different friction coefficients between particles on the ALPSI. Figure 12. Effect of different friction coefficients between particles on velocity distribution: (a) vertical section and (b) bottom.

Figure 13. Effect of different friction coefficients between particles on the ALPSI.

Figure 14. Effect of different friction coefficients between particles and the wall on the LPSI: (a) 0.05, (b) 0.25, (c) 0.45, (d) 0.65, and (e) 0.85.
The friction coefficient between particles is increased from 0.15 to 0.95, with an interval of 0.2. It can be seen from Figure 11 that with the increase in the friction coefficient, the colors of the grids near the wall and at the bottom become darker. This shows that with the increase of the friction coefficient, the percolation near the wall and at the bottom increases.

Figure 12 shows the effect of different friction coefficients between particles on velocity distribution. It can be seen from Figure 12 that with the increase in the friction coefficient, the stream velocity decreases and the velocity gradient near the wall and at the bottom decreases. Combined with Figure 11, it can be seen that the percolation did not increase with the velocity gradient. This is because, with the increase in the friction coefficient, the interaction between the particles is enhanced, large gaps are more easily formed, and the percolation is enhanced.

Figure 13 shows the effect of different friction coefficients between particles on the ALPSI. It can be seen from Figure 13 that with the increase in the friction coefficient, the ALPSI of the near-wall and bottom regions shows an increasing trend. When the friction coefficient increases from 0.15 to 0.95, the ALPSI of the near-wall region increases from 0.016 to 0.044 and that of the bottom region increases from 0.021 to 0.048.

5.4. Friction Between Particles and the Wall. Figure 14 shows the effect of different friction coefficients between particles and the wall on the LPSI. The friction coefficient between particles and the wall is increased from 0.05 to 0.85, with an interval of 0.2. It can be seen from Figure 15 that with the increase in the friction coefficient, the stream velocity decreases and the velocity gradient near the wall and at the bottom decreases. Combined with Figure 11, it can be seen that the percolation did not increase with the velocity gradient. This is because, with the increase in the friction coefficient, the interaction between the particles is enhanced, large gaps are more easily formed, and the percolation is enhanced.

Figure 16 shows the effect of different friction coefficients between particles and the wall on velocity distribution. It can be seen from Figure 16 that with the increase in the friction coefficient, the stream velocity decreases and the velocity gradient near the wall and at the bottom decreases. Combined with Figure 11, it can be seen that the percolation did not increase with the velocity gradient. This is because, with the increase in the friction coefficient, the interaction between the particles is enhanced, large gaps are more easily formed, and the percolation is enhanced.

Figure 17 shows the effect of different fine particle mass fractions on the LPSI. It can be seen from Figure 17 that with the increase in the fine particle mass fraction, the LPSI of the near-wall and bottom regions shows an increasing trend. When the fine particle mass fraction increases from 5% to 25%, the LPSI of the near-wall region increases from 0.016 to 0.044 and that of the bottom region increases from 0.021 to 0.048.

5.5. Friction Between Particles and the Wall. Figure 18 shows the effect of different fine particle mass fractions on the ALPSI. It can be seen from Figure 18 that with the increase in the fine particle mass fraction, the ALPSI of the near-wall and bottom regions shows an increasing trend. When the fine particle mass fraction increases from 5% to 25%, the ALPSI of the near-wall region increases from 0.016 to 0.044 and that of the bottom region increases from 0.021 to 0.048.
with an interval of 0.2. It can be seen from Figure 14 that when the friction coefficient is less than 0.25, the colors of the grids near the wall approach white. This shows that there is no obvious percolation near the wall. This is because when the friction coefficient is less than 0.25, the wall is sufficiently smooth and there is no shear zone near the wall.60 The effect of different friction coefficients between particles and the wall on velocity distribution in the vertical section is shown in Figure 15a. When the friction coefficient is greater than this critical value, yellow grids appear near the wall and the colors deepen with the friction coefficient. This is because, with the increase in the friction coefficient, the shear zone is formed, stream velocity near the wall decreases, the velocity gradient increases, and the percolation increases. When the friction coefficient increases from 0.05 to 0.25, the dark yellow and red grids at the bottom converge toward the center. This is because the stream velocity near the wall decreases and the velocity gradient at the center increases. The effect of different friction coefficients between particles and the wall on velocity distribution at the bottom is shown in Figure 15b. When the friction coefficient is greater than this critical value, the number of dark yellow and red grids at the bottom decreases. This is because the percolation near the wall increases the fine particle mass fraction at the bottom, the porosity decreases, and the percolation is hindered. By comparing Figure 14 with other figures (Figures 5, 8, and 11), it can be found that although other factors also affect the percolation near the wall, their effect is weak, and they are not sufficient to cause obvious changes in the porosity at the bottom.

Figure 16 shows the effect of different friction coefficients between particles and the wall on the ALPSI. It can be seen from Figure 16 that with the increase in the friction coefficient, the ALPSI of the near-wall region increases and that of the bottom region decreases. When the friction coefficient increases from 0.05 to 0.85, the ALPSI of the near-wall region increases from 0.005 to 0.055 and that of the bottom region decreases from 0.045 to 0.034.

5.5. Fine Particle Mass Fraction. Figure 17 shows the effect of different fine particle mass fractions on the LPSI. The fine particle mass fraction is increased from 5 to 25%, with an interval of 5%. It can be seen from Figure 17 that the number of dark yellow and red grids near the wall and at the bottom decreases with the fine particle mass fraction. This is because, with the increase in the fine particle mass fraction, the porosity decreases and the percolation of fine particles is hindered. These phenomena correspond to the effect of fine particle mass fraction on segregation.27

Figure 18 shows the effect of different fine particle mass fractions on the ALPSI. It can be seen from Figure 18 that with the increase in the fine particle mass fraction, the ALPSI of the near-wall and bottom regions decreases linearly. When the fine particle mass fraction increases from 5 to 25%, the ALPSI of the near-wall region decreases from 0.053 to 0.027 and that of the bottom region decreases from 0.066 to 0.017.

5.6. Fine Particle Size. Figure 19 shows the effect of different fine particle sizes on the LPSI. The diameter of fine particles is increased from 2 to 5 mm, with an interval of 1 mm. It can be seen from Figure 19 that the colors of grids near the wall and at the bottom gradually approach white with the fine particle size. This is because the smaller the ratio of the diameter of the fine particles to the coarse particles, the easier it is for fine particles to pass through the gaps between coarse particles and percolation occurs. When the difference in particle size decreases, the percolation becomes difficult and the percolation strength decreases. This is consistent with previous results on segregation.27,33,61

Figure 20 shows the effect of different fine particle sizes on the ALPSI. It can be seen from Figure 20 that the ALPSI of the near-wall and bottom regions decreases with the fine particle size. When the diameter of fine particles increases from 2 to 5 mm, the ALPSI of the near-wall region decreases from 0.041 to 0 and that of the bottom region decreases from 0.039 to 0.

6. CONCLUSIONS

In this work, percolation of a binary particle mixture in a rectangular hopper with inclined bottom is studied based on DEM. A local percolation strength index (LPSI) is proposed,
and the percolation strength grid maps are drawn. The effects of orifice width, angle, friction between particles, friction between particles and the wall, fine particle mass fraction, and fine particle size on local percolation are revealed.

During the discharging process, apart from the free surface, the percolation of the binary particle mixture in the hopper is mainly concentrated near the wall and at the bottom. The average local percolation strength index (ALPSI) of the near-wall region and the bottom region is calculated. The larger the orifice width, the larger the ALPSI of the near-wall region and the smaller the ALPSI of the bottom region. The percolation of the near-wall region is not sensitive to the angle, and the ALPSI of the bottom region decreases with the angle. The effect of friction on percolation is significant. The percolation strength increases with the friction coefficient between particles. With the increase in the friction coefficient between particles and the wall, the percolation strength near the wall increases, while that in the bottom region decreases. With the increase in the fine particle mass fraction and the decrease of the difference in particle size, the percolation strength decreases.

Based on the above conclusions, the LPSI can accurately reflect the location and strength of percolation. The current work provides an effective reference method for further understanding segregation, especially in key application fields such as pharmacy, metallurgy, and chemistry that require high-uniformity prediction.

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Notes
The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work was supported and encouraged by the National Key R&D Program of China (2017YFB0603504-2) and Shandong Provincial Natural Science Foundation, China (ZR2017LEE019 and ZR2014EL030).

■ NOMENCLATURE

df diameter of fine particles (mm)
E Young’s modulus (Pa)
e restitution coefficient
F contact force (N)
f, friction coefficient
G shear modulus (Pa)
g acceleration of gravity (kg m/s²)
I moment of inertia (kg m²)
k number of particles in contact with particle i
M fine particle mass fraction (%) m mass of particle (kg)
N number of effective grids
nc number of coarse particles in the grid
nf number of fine particles in the grid
r radius of particle (m)
S number of sampling time points
T torque (N m)
t sampling time point
Vc average velocity of coarse particles in the grid (m/s)
Vi average velocity of fine particles in the grid (m/s)
v translational velocity of a particle (m/s)
vce velocity of coarse particle i in the grid
vfi velocity of fine particle i in the grid
W orifice width (mm)

■ GREEKS

β damping coefficient
δ overlap (m)
θ angle (°)
λ Poisson ratio
ρ density (kg/m³)
ω rotational velocity (rad/s)
ω̇ unit rotational velocity vector (rad/s)

■ SUBSCRIPTS AND SUPERSCRIPTS

c contact
d damping
i particle i
ij between particles i and j
j particle j
n normal
p particle
pp between particles
pw between particles and the wall
s spring
t tangential
w wall
* equivalent

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