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Particles segregation in rotating drum based on discrete element method

Wu Li Huang Peng Fu Shuaiqi

(School of Mechanical Engineering, Southeast University, Nanjing 211189, China)

Abstract: In order to study particle segregation in the rotating drum, the movement of particles is studied by theoretical deduction and numerical simulation. According to the theoretical deduction, particles near the end wall are lifted higher by the friction of the end wall, which leads to small particles gathering in the middle of the drum. The model of particle motion is established based on the discrete element method. It can be shown from the simulation results that the particles accumulated higher near the end wall, which is consistent with the theoretical deduction. In addition, the effects from the aspects of the relative friction between particles, the friction between the end wall and particle, the drum aspect ratio and the rotation speed were explored by the simulation. From the simulation results, it can be pointed out that the friction of the end wall has a decisive influence on the axial segregation of the particles, and the other factors merely affect the accumulate forms of particles.

Key words: discrete element method; granular material; axial segregation

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Granular material is a kind of material that is widely found in nature, such as sand, small stones, debris etc. The characteristic of particle motion is similar to both that of the solid and liquid materials[1]. The mixing and separating of particles are found in the industry of mining, food, pharmaceutical processing, metallurgy, etc[2]. Segregation of particles is an important phenomenon in the particle motion process. The segregation refers to the fact that different kinds of well-mixed particles will display a strange phenomenon during the motion; i.e., the same kind of particles will be collected together[3-5]. The segregation of particles was first proposed by Koyama in 1939. The study on particles is difficult to carry out in depth due to the complexity of particle motion. In recent years, with the development of computer technology, a variety of simulation approaches are used to study the movement of particles. Maione et al.[6] used the method of simulation and experiment to study the segregation of cylindrical wood pellets and spherical steel particles in the rotating cylindrical drums. The view that the difference in densities will lead to particle segregation has been put forward. Deng et al.[7] studied the segregation phenomenon of two kinds of particles which are different in size by experimental and numerical simulation, and pointed out that the differences in the particle size and the structure of containers will cause the segregation of particles. Cui et al.[8-9] studied the particle motion in the ball mill and suggested that particle segregation will occur in the ball mill. Moreover, the contact between the end wall and particles as well as the rotation speed was proved to affect the segregation forms of particles in Ref. [9].

In this paper, the simulation and theoretical deduction are combined to study the segregation of the binary mixed particles in the horizontal rotating drum. The view that the friction between the end wall and particles is the main factor that causes axial segregation is proposed. Other factors such as the rotation speed of the drum, the aspect ratio etc. can only affect the segregation band forms.

1 Analysis of Single Particle Motion

Due to the large number of particles in the drum, unforeseen collisions and vibrations will occur during the motions. It is difficult to analyze all the particles in the whole drum by the theoretical method. This section explores the tendency of particle motion in the drum by studying the motion of the single particle.

1.1 Effect of end wall friction on particle lifting

The motion of the single particle in the drum is divided into three stages: acceleration stage, constant stage, deceleration and throwing stage, as shown in Fig. 1.

Fig. 1 is the diagram of single particle motion, where α is the particle's position.

1) Accelerating stage (O-A)

During this stage, the friction between the particle and drum provides power for the particle. The motion function is

$$\left.\begin{aligned}\mu N+\mu F_{\mathrm{t}}-G\sin\alpha=ma\\ N-G\cos\alpha=m\omega^2R\end{aligned}\right\}\tag{1}$$

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Biographies: Wu Li (1992—), male, graduated; Huang Peng (corresponding author), male, doctor, associate professor, huangpeng@seu.edu.cn.

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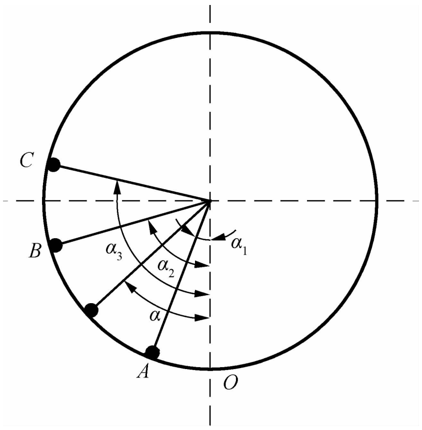


Fig. 1 Diagram of single particle motion in the drum

where m is the mass of particle; G is the gravitational force of particle; N is the pressure between the particle and drum; a is the linear acceleration of particle; ω is the angular velocity of particle; R is the radius of drum; F_t is the simplified constant axial force; μ is the comprehensive friction coefficient, which multiplies positive force equal to the comprehensive friction force.

2) Constant stage (A-B)

During this stage, the particle is in a state of constant speed, $\omega = \omega_c$, and ω_c is the angular velocity of the drum. The particle and the cylinder wall are relatively static. The friction between the drum and particle is a static friction, which is balanced with the resistance caused by gravity.

3) Deceleration and throwing stage (B-C)

During this stage, the friction force still provides power for particles, but it is not enough to overcome the resistance caused by the gravity. At point C, pressure N between the particle and drum is 0. The particle will be dropped after point C.

$$\left.\begin{aligned} \mu N + \mu F_t - G\sin\alpha = ma \\ N - G\cos\alpha = m\omega^2 R \end{aligned}\right\} \tag{2}$$

The direction of a in Eq. (1) is the same as the velocity direction, but it is opposite to the velocity direction in Eq. (2).

Take a small time step Δt and assume that the speed changes steadily in one time step. After calculation, update the variables in the equations and repeat in the next step.

Let $N \leqslant 0$ be the separate condition and $F_t = 0$ when ignoring the end wall friction.

The initial values of variables are as follows: $\Delta t = 0.01$ s, $\alpha = 0$, $\omega = 0$, $\omega_c = 5.2$ rad/s, $a = 0$, $g = 9.8$ m/s^2, $\mu = 0.3$, $F_t = 3$ mg, and $R = 0.2$ m.

When considering the friction between the particle and end wall ($F_t \neq 0$), the lifting angle $\alpha_3 = 108.29°$; and when ignoring the friction from the end wall, the lifting angle $\alpha_3 = 96.32°$. The results show that the lifting angle is larger when there is a friction between the end wall and particle. So, the height of the particle accumulation is higher when the end wall is rough, as shown in Fig. 2, where h_M is the accumulation height in the middle of the drum; h_E is the accumulation height near the end wall.

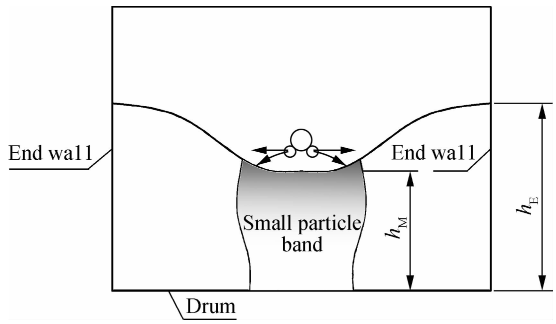


Fig. 2 Accumulation height of particles

1.2 Effects of collisions on axial velocity of particles

In the process of throwing, the trajectory of particles is perpendicular to the axis of the drum before collision, and the axial velocity of particles is zero.

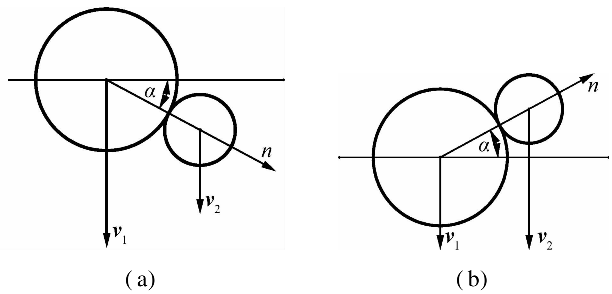


Fig. 3 Diagram of collision

The mass of the large particle is m_1, and the mass of the small particle is m_2. When the large particle's diameter is 2 times that of the small particle, then $m_1 = 8m_2$. Assume that collision occurs on the right side of the large particle. If $v_1 > v_2$, then the large particle hits the small particle; and if $v_1 < v_2$, the small particle hits the large particle.

The particle momentum conserves along the public line n of particles during the collision.

According to the law of the momentum conservation and definition of the recovery coefficient:

$$e = \frac{v'_{2n} - v'_{1n}}{v_{1n} - v_{2n}} \tag{3}$$

$$m_1 v_{1n} + m_2 v_{2n} = m_1 v'_{1n} + m_2 v'_{2n} \tag{4}$$

The velocity after collision can be solved as

$$v'_{2n} = \frac{8}{9}v_{1n} + \frac{1}{9}v_{2n} + \frac{8}{9}ev_{1n} - \frac{8}{9}ev_{2n} \tag{5}$$

$$v'_{1n} = \frac{8}{9}v_{1n} + \frac{1}{9}v_{2n} - \frac{1}{9}ev_{1n} + \frac{1}{9}ev_{2n} \tag{6}$$

where $v_{1n} = v_1 \sin\alpha$; $v_{2n} = v_2 \sin\alpha$; and e is the recovery coefficient.

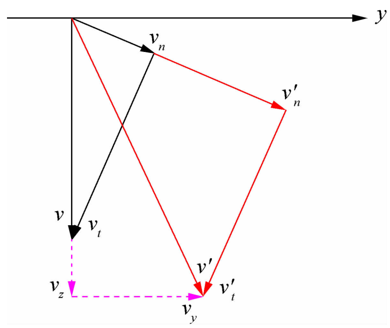


Fig. 4 Diagram of the speed changing under the condition of large particle hitting small particle

In Fig. 4, y is the axial direction of the drum. v, v_n, v_t, respectively, represents the actual velocity, the velocity component in the n direction and the velocity component in the t direction before collision. v', v'_n, v'_t, respectively, represents the actual velocity, the velocity component in the n direction and the velocity component in the t direction after collision. The velocity component in the t direction does not change after collision. v_y and v_z are the velocities in the axial direction of the drum and perpendicular to the axial direction of the drum. As shown in Fig. 4, the velocity component in the axial direction before collision is zero. The lateral velocity v_n becomes larger after collision, so the velocity component v_y in the axial direction is not equal to zero, and the axial velocity of particles is generated. It can also be found that v_y will be larger if v'_n becomes larger. The v_n of small particles increases a lot and the velocity of large particles changes slightly. Therefore, small particles will obtain the axial velocity while the axial velocity of large particles remains almost zero after collision.

Similarly, for the small particle colliding with the large particle, the velocity after collision can be solved as

$$v'_{2n} = \frac{8}{7}v_{1n} + \frac{1}{7}v_{2n} - \frac{8}{7}ev_{1n} + \frac{8}{7}ev_{2n} \tag{7}$$

$$v'_{1n} = \frac{8}{7}v_{1n} + \frac{1}{7}v_{2n} - \frac{1}{7}ev_{1n} - \frac{1}{7}ev_{2n} \tag{8}$$

The velocity of large particles changes little, while the velocity of small particles changes significantly. The particle's lateral velocity v_{2n} becomes smaller after collision as $v_1 < v_2$. The change of speed is shown in Fig. 5.

The symbols in Fig. 5 are the same as those in Fig. 4. As can be seen from Fig. 5, since v_n becomes smaller, the axial velocity component v_y is generated. The smaller the v'_n, the larger the v_y will be. In the collision, large particles' velocity changes little but small particles' velocity changes significantly. Therefore, the axial velocity component of large particles is almost zero, and small particles will obtain a large axial velocity.

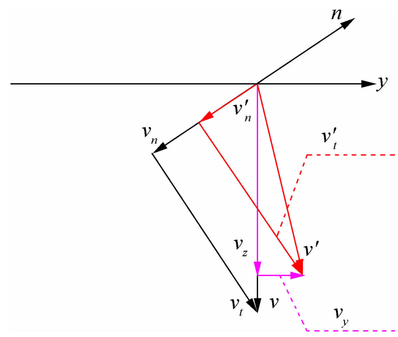


Fig. 5 Diagram of the speed changing under the condition of small particles hitting large particles

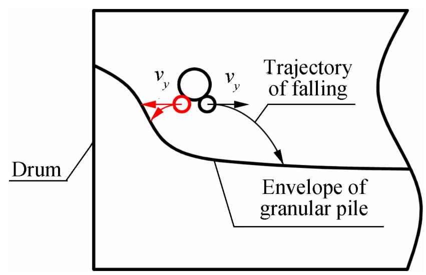


Fig. 6 Collision near end wall

Taking the collision between large particles and small particles as an example, when the small particle is on the right side of the large particle, the small particle will obtain an axial velocity towards the right side. When the small particle is on the left side of the large particle, it will obtain an axial velocity towards the left side. Which side of large particles will be hit is completely random. Since there is a slope near the end wall, small particles can move a long distance in the axial direction towards the middle of the drum. On the other hand, if small particles move towards to the end wall, they will fall on the particle pile just after a short distance. Therefore, small particles will gather to the middle of the drum. Besides, small particles cannot move to the end wall from the middle of the drum due to the blocking of the accumulated particles. Thus, small particles accumulate in the middle of the drum.

2 Simulation and Results

2.1 Simulation design

The discrete element method is a numerical method for simulating motion and interaction of discrete entities[10-13]. It was first proposed by Cundall and Stark in 1971. In this paper, simulation is designed based on the discrete element method. Groups A and B are set to verify the effect of the friction between the end wall and particles on segregation. The material properties of the drum and particles are shown in Tab. 1, Tab. 2 and Tab. 3. In Group A and Group B, the size of the drum is set to be 360 mm × 400 mm. The diameter of large particles is 8 mm; the diameter of small particles is 4 mm; the rotation

Tab. 1 Properties of drum and particles

Material properties	Drum body/End wall	Particles
Density/(kg · m^{-3})	7 800	2 500
Shear modulus/MPa	7×10^4	25. 73
Poisson's ratio	0. 3	0. 25

speed is set to be 60 r/min; and the numbers of large particles and small particles are both 13 000; the recovery coefficient between the particles and drum is 0. 97.

Tab. 2 Parameters of Group A

Slide					Roll				
f_{ss}	f_{sb}	f_{sw}	f_{bw}	f_{bb}	f_{ss}	f_{sb}	f_{sw}	f_{bw}	f_{bb}
0. 5	0. 5	0. 5	0. 5	0. 5	0. 3	0. 3	0. 3	0. 3	0. 3

In Tab. 2, the friction coefficient between particles and end wall is the same as that between particles and the drum body. f_{ss} is the friction coefficient between the small particle and small particle; f_{sb} is the friction coefficient between the small particle and large particle; f_{bb} is the friction coefficient between the large particles; f_{bw} is the friction coefficient between the large particle and drum body; f_{sw} is the friction coefficient between the small particle and drum body.

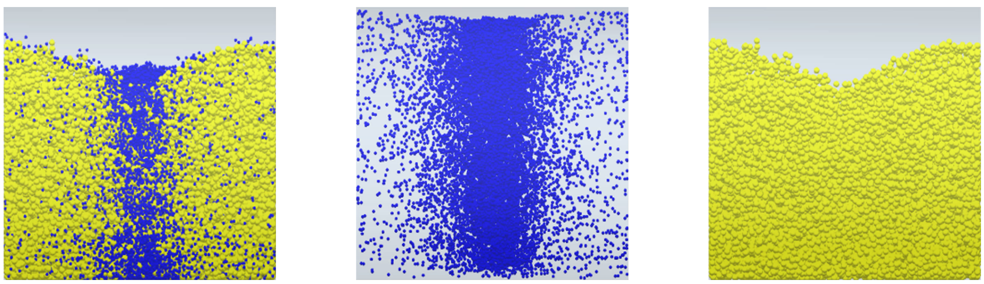
Tab. 3 Parameters of Group B

Slide			Roll		
f_{pp}	f_{pt}	f_{pw}	f_{pp}	f_{pt}	f_{pw}
0. 5	0. 5	0. 1	0. 3	0. 3	0. 01

In Tab. 3, the friction of particles are all the same. f_{pp} is the friction coefficient between the particles; f_{pt} is the friction coefficient between the particle and drum body; f_{pw} is the friction coefficient between the particle and end wall.

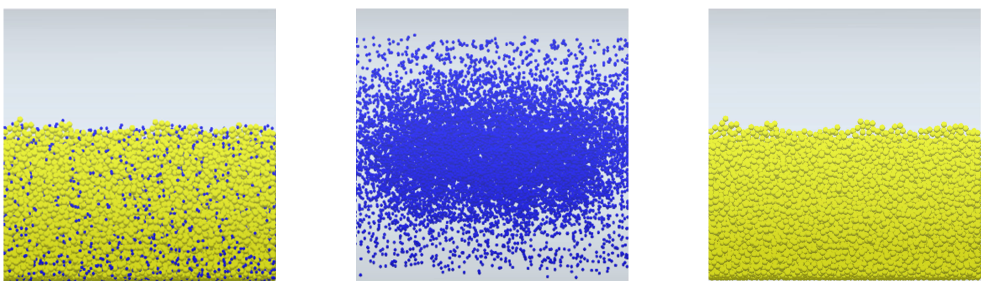
2. 2 Simulation results

Simulation results of Group A and Group B are shown in Fig. 7 and Fig. 8, respectively, where the yellow particles represent large particles and blue particles represent small particles.



(a) (b) (c)

Fig. 7 Results of Group A with a rough end wall. (a) Mixture of particles; (b) Hidden large particles; (c) Hidden small particles



(a) (b) (c)

Fig. 8 Results of Group B with a smooth end wall. (a) Mixture of particles; (b) Hidden large particles; (c) Hidden small particles

Comparing Fig. 7(a) with Fig. 8(a), it can be found that when the end wall is rough, the accumulation of particles at the end wall is higher than that in the middle of the drum. When the end wall friction is ignored, the height of the stack at the end wall and that in the middle of the drum is the same, as shown in Fig. 8(a). Fig. 7(b) and Fig. 8(b) give the results when large particles are hidden. It can be seen that the small particles of Group A are aggregated to the middle of the drum, forming a small particle band. Small particles in Group B are evenly distributed along the axial direction. As shown in Fig. 7(c) and Fig. 8(c), large particles are evenly distributed in the axial direction except the higher accumulation near the end wall in Group A, which is consistent with the theoretical derivation.

3 Effects of Other Factors on Segregation

3. 1 Design of simulation experiments

Simulation results of Group A and Group B show that, when the end wall is rough, particles near the end wall will be lifted higher than that in the middle of the drum, which will lead to the accumulation of small particles. In this section, the effects of the friction between particles and the aspect ratio of the drum are studied.

The diameter of large particles is 8 mm and that of small particles is 4 mm. Parameters of different groups are shown in Tab. 4.

The drum used in Groups F, G and H is set to be 360 mm × 700 mm while the other groups are set to be 360 mm × 400 mm.

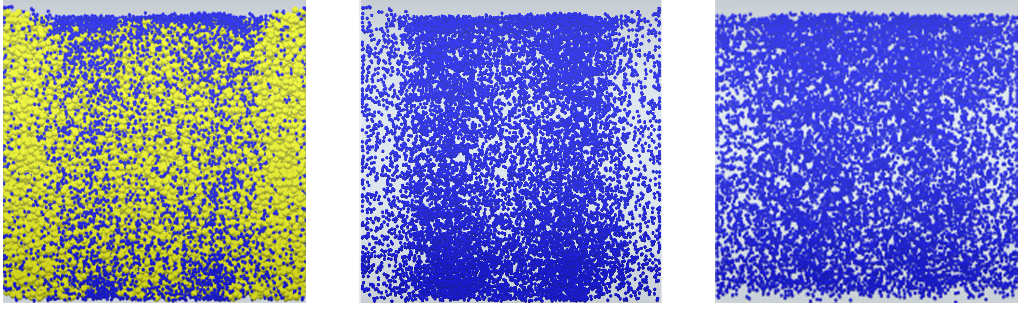
Tab. 4 Parameters of different groups

Parameters		A	C	D	E	F	G	H
Drum length L/mm		400	400	400	400	700	700	700
Drum diameter D/mm		360	360	360	360	360	360	360
Slide	f_{ss}	0.5	0.8	0.5	0.5	0.5	0.5	0.3
	f_{sb}	0.5	0.8	0.8	0.5	0.5	0.5	0.3
	f_{sw}	0.5	0.8	0.5	0.5	0.5	0.5	0.5
	f_{bw}	0.5	0.5	0.8	0.5	0.5	0.5	0.5
	f_{bb}	0.5	0.5	0.8	0.5	0.5	0.5	0.3
Roll	f_{ss}	0.3	0.5	0.3	0.3	0.3	0.3	0.1
	f_{sb}	0.3	0.5	0.5	0.3	0.3	0.3	0.1
	f_{sw}	0.3	0.5	0.3	0.3	0.3	0.3	0.3
	f_{bw}	0.3	0.3	0.5	0.3	0.3	0.3	0.3
	f_{bb}	0.3	0.3	0.5	0.3	0.3	0.3	0.1
Rotation speed/($r \cdot min^{-1}$)		60	60	60	30	60	70	70
Total number/10^3		26	26	26	26	52	52	52

3.2 Analysis of simulation results

The simulation results of Groups C, A and D are shown in Fig. 9, Fig. 10 and Fig. 11.

From Figs. 9 to 11, it can be seen that under the condition of the parameters' setting in Tab. 4, small particles in each group are gathered during the motion. Comparing the results of these three groups, it can be found that there are two small particle bands when the friction coefficient of small particles is greater than that of large particles, but the particle band is not concentrated, as shown in Fig. 9. When the friction coefficient of the small particle is equal to that of large particles, there is one concentrated small particle band, as shown in Fig. 10. When the friction coefficient of larger particles is greater, the band is represented in the form of a trapezoidal concentrated band with a narrow width on the lower side and a wide width on the upper side, as shown in Fig. 11. The upper and lower above refer to upstream and downstream of the particle stream.



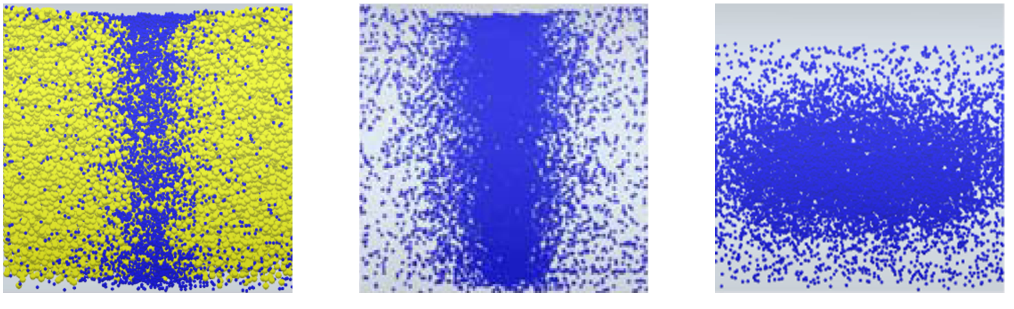
(a) (b) (c)

Fig. 9 Results of Group C with a friction coefficient of small particles greater than that of large particles. (a) Mixture of particles; (b) Hidden large particles; (c) Smooth end wall

Combining Fig. 9(c), Fig. 10(c) and Fig. 11(c), it can be found that no matter under what kind of conditions, small particles are evenly distributed along the axial direction when there is no friction between the end wall and particles, which is consistent with the theoretical results.

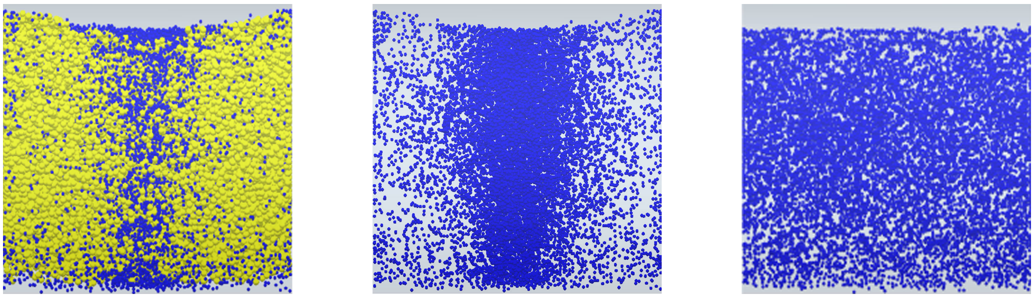
The rotation speed is changed from 60 to 30 r/min and the results are shown in Fig. 12.

As shown in Fig. 12, large particles appear on the surface while the small particles are almost in the internal part. When large particles are hidden, it can be found that small particles gather in the middle of the drum in the form of a particle cluster, rather than a small particle band.



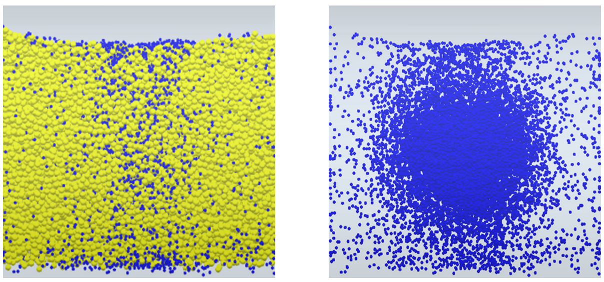
(a) (b) (c)

Fig. 10 Results of Group A with the friction coefficient of small particles equal to that of large particles. (a) Mixture of particles; (b) Hidden large particles; (c) Smooth end wall



(a) (b) (c)

Fig. 11 Results of Group D with the friction coefficient of large particles greater than that of small particles. (a) Mixture of particles; (b) Hidden large particles; (c) Smooth end wall



(a) (b)

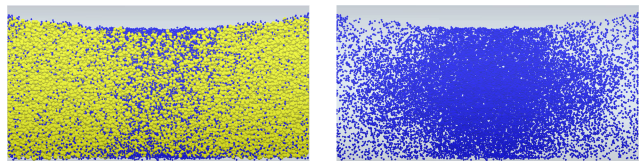
Fig. 12 Segregation at the low speed of Group E. (a) Mixture of particles; (b) Hidden large particles

In Groups C, A, D and E, it can be concluded that if there is a friction between the end wall and particles, small particles will gather no matter under what kind of conditions. When the rotation speed is high, friction will appear in the form of a small particle band; when the speed is slow, small particles gather in the form of a particle cluster. When one small particle band or cluster is represented, the small particles gather in the middle of the drum. When two small particle bands are represented, the small particle bands are symmetrically distributed in the middle of the drum.

The differences among the four groups only affect the forms of aggregation, which do not affect whether small particle aggregation occurs or not. Thus, it can be concluded that the friction of the end wall has a decisive effect on the appearance of the segregation under the same condition.

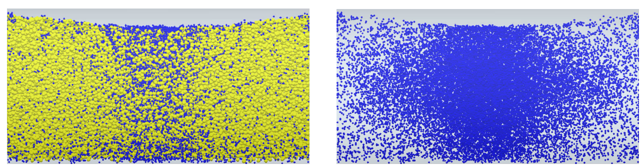
In order to explore the effect of the aspect ratio on particle segregation, the drum is set to be 360 mm × 700 mm in Groups F, G and H. Group F changes the 360 mm × 400 mm-drum to 360 mm × 700 mm-drum based on Group A; Group G changes its rotation speed from 60 to 70 r/min based on Group F; Group H is set under the condition that the friction coefficient between particles is smaller. The results of three groups are shown in Fig. 13, Fig. 14 and Fig. 15, respectively.

Comparing the results of three groups above, it can be found that in the case of a large aspect ratio, particle segregation will also appear. And the particle band is not concentrated. The increase of the rotation speed will make particle band a little more concentrated. Two concentrated



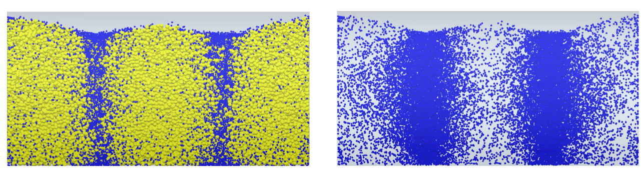
(a) (b)

Fig. 13 Results of Group F with a rotation speed of 60 r/min. (a) Mixture of particles; (b) Hidden large particles



(a) (b)

Fig. 14 Results of Group G with a rotation speed of 70 r/min. (a) Mixture of particles; (b) Hidden large particles



(a) (b)

Fig. 15 Results of Group H with a smaller friction between particles. (a) Mixture of particles; (b) Hidden large particles

particle bands appear when the friction coefficient between particles is smaller than that between the particles and the end wall.

The simulation results of each group show that the friction of the end wall has a decisive influence on the appearance of particle segregation. When there is friction between the end wall and particles, particles in the drum will segregate, and small particles will appear in the form of a particle band along the axial direction. Changing the friction between particles, the drum length and rotation speed do not affect the emergence of the particles band,

and only affect the form of the particle band. When the friction does not exist between the end wall and particles, there will be no segregation no matter under what kind of conditions.

4 Conclusion

In this paper, the phenomenon of particle segregation in a rotating drum was studied by theoretical deduction and simulation. Theoretical analysis shows that the friction of the end wall makes particles near the end wall be lifted higher, and a slope will appear in the end of the drum. The particle collision analysis shows that only small particles can obtain a higher axial speed, which causes small particles to accumulate in the middle of the drum in the form of a particle band. Simulation experiments results verified the conclusion. It can be concluded from the simulation and theoretical deduction that the friction of the end wall has a decisive influence on the axial segregation. The factors, except for the friction of the end wall, only affect the forms of particle aggregation, and the occurrence of segregation cannot be decided by these factors.

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基于离散元素法的滚筒内颗粒物质分层现象

伍 力 黄 鹏 付帅旗

(东南大学机械工程学院, 南京 211189)

摘要:为了研究颗粒物质在旋转滚筒中出现的分层现象,从理论推导和数值模拟2个方面对颗粒物质的运动进行了研究.理论推导指出端盖的摩擦会使得靠近端盖处颗粒提升高度变高,由此引起小颗粒在滚筒中部聚集,出现颗粒分层现象.基于离散元素法建立了颗粒在滚筒中运动的模型,当端盖摩擦较大时,颗粒在端盖处堆积较高,并且在滚筒中部出现小颗粒聚集,与理论推导结果相符.此外,模拟实验从颗粒间的相对摩擦大小、端盖对颗粒摩擦大小、滚筒长径比以及滚筒转速等几个方面研究了颗粒分层的情况.模拟实验结果表明:端盖的摩擦对颗粒轴向分层有决定性影响,其余因素只会对颗粒的聚集形态产生影响.

关键词:离散元素法;颗粒物质;轴向分层

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