DEM SIMULATION OF PARTICLE SIZE SEGREGATION BEHAVIORS DURING SCREW DISCHARGING INSIDE THE COREX PRE-REDUCTION SHAFT FURNACE[1]

Kou Mingyin[2]
Wu Shengli[2]
Xu Jian[2]
Guo Xinying[2]
Du Kaiping[2]
Sun Jing[2]

Abstract

Pre-reduction shaft furnace in Corex process uses screws to discharge burdens into the melter gasifier. However, the uneven screw discharging method in circumferential direction leads to the burden velocity segregation behaviors, which results in the redistribution of burden particles, thus directly affecting the gas distribution inside pre-reduction shaft furnace. Based on DEM, a three dimensional model is established in present work to investigate the particle size segregation behaviors (PSSB) during screw discharging process, which has been little studied before. The DEM base model is adapted to determine the effects of pre-reduction shaft furnace bottom diameter, screw casing diameter as well as screw rotating rate on burden descending velocity and PSSB. The pre-reduction shaft furnace bottom diameter influences the burden velocities most in edge area while almost makes no difference on the central area. To increase the screw casing diameter or the screw rotating speed increase the burden velocities in all areas and the increment is biggest for the edge area in the case of screw casing diameter while it almost keeps the same amplitude for all areas in the case of screw rotating diameter. To increase the furnace bottom diameter and to enlarge the screw casing diameter, or to decrease the screw rotating speed help to obtain a relatively uniform RPS distribution during discharging.

Key words: Pre-reduction shaft furnace in Corex; Screw discharging; Particle size segregation; DEM simulation.

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[2] *State Key Laboratory of Advance Metallurgy, University of Science and Technology Beijing, China; School of Metallurgical and Ecological Engineering, University of Science and Technology Beijing, China.*

1 INTRODUCTION

Screw feeders are usually applied in the field of mineral processing and agriculture industries in order to transfer the materials from hoppers or bins to the next container. The screw used in above areas is a single one in most cases, the mechanism and the behaviors of discharging materials have also been investigated by previous researchers.[1-4] As for the ironmaking process, there is a Corex process which uses screws to discharge burdens from the bottom of pre-reduction shaft furnace into the melter gasifier. Unlike the single screw used in hoppers or bins, the number of screws applied in the pre-reduction shaft furnace is eight, and these screws symmetrically distributed around the centerline of pre-reduction shaft furnace. Due to the short history, the mechanism and the burden movement behaviors in case of eight screws have rarely been studied before. Similarly to hoppers or bins with one screw, the pre-reduction shaft furnace also has the problems such as the velocity segregation and particle size segregation behaviors (PSSB) during screws discharging. These problems have effects on the gas distribution inside the pre-reduction shaft furnace, and then affect the reduction degrees of iron ores. So it is necessary to study the burden movement behaviors during screws discharging.

Since Discrete Element Method (DEM) is one of the most reliable simulation methods for granular movement characteristics,[5] previous DEM researches have been applied to studying the rotation of screw conveyer,[1-4] and also to investigating the burden behaviors during discharging from the top bunker and charging into the blast furnace in ironmaking process.[6-8] However, little study has been performed on the burden movement behaviors discharging from the pre-reduction shaft furnace by eight screws, which is the right purpose of this work. So the present work adopt DEM to determine the effects of furnace bottom diameter, screw casing diameter and screw rotating rate on the burden descending velocity and PSSB.

2 DEM SIMULATION

DEM simulation takes granular burden as individual particles, and set up a particle-particle contact model to study particle’s movement in both normal and shear direction according to Newton’s second law of motion. The particle-particle contact model consists of spring and dashpot in the normal direction, spring, dashpot and slider in the shear direction (Figure 1).

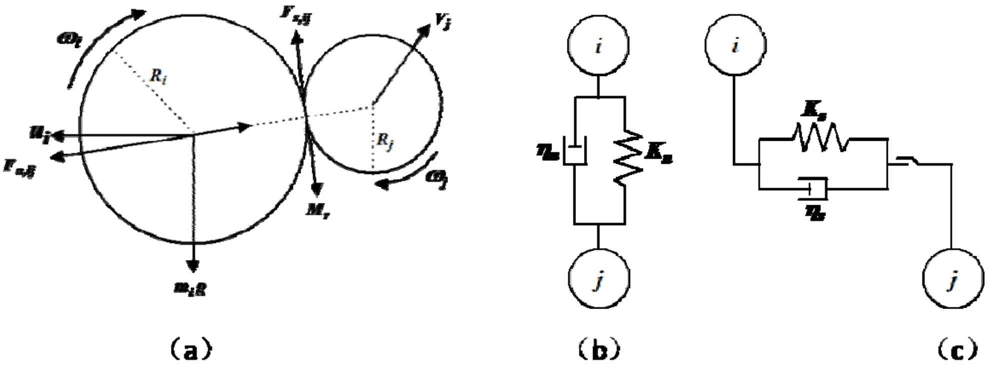


Figure 1. (a) the contact model between particle i and j (b) forces in normal direction (c) forces in shear direction.

The contact forces in normal and shear direction can be expressed by Equations 1 and 2.

$$m\frac{dv}{dt}=\sum F_n \tag{1}$$

$$I\frac{dw}{dt}=\sum F_s \tag{2}$$

Where, m, v, I and ω are the mass of the particle, velocity, inertia moment and the angular velocity, respectively. F_n and F_s are the normal and shear forces between particle i and j, the subscript n and s denote the normal and shear. And the two direction forces can be expressed by Equations 3 and 4.

$$F_{n,ij}=(K_n\Delta u_{n,ij}+\eta_n\frac{\Delta u_{n,ij}}{\Delta t})\times\mathbf{n}_{ij} \tag{3}$$

$$F_{s,ij}=\min\{[K_s(\Delta u_{s,ij}+\Delta\phi_{ij})+\eta_s\frac{(\Delta u_{s,ij}+\Delta\phi_{ij})}{\Delta t}]\times\mathbf{s}_{ij}\} \tag{4}$$

Where, K and η are stiffness and damping coefficient respectively. Δu_{ij} and $\Delta\phi_{ij}$ represent the relative translational and tangential displacement of gravitational center between particle i and j, respectively. n_{ij} and s_{ij} are unit vector from i-th particle to j-th particle in normal and shear components.

Figure 2 demonstrates the physical model studied in this work, which is a simplified pre-reduction shaft furnace of Corex.

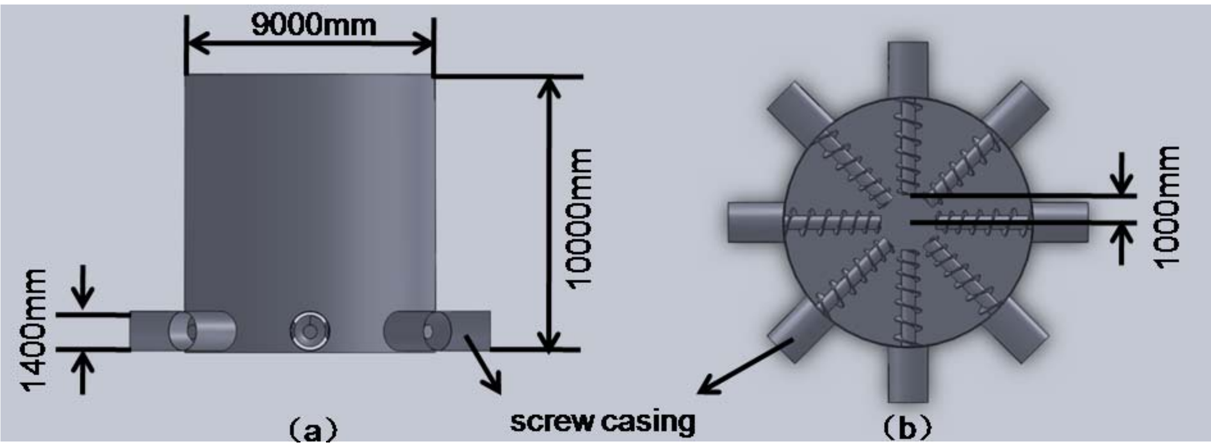


Figure 2. The schematic diagram of pre-reduction shaft furnace model simulated in this paper. (a) front view (b) top view.

The furnace is 10 m high with the diameter of 9 m. Eight screws with the same size are installed symmetrically around the centerline at the bottom of this cylinder, and the distance between the centerline and the start end of screws is 1,000 mm. The casing diameter in this model is 1,400 mm. The screw schematic diagram is shown in Figure 3, and the parameters of screws used in this model are shown in Table 1.

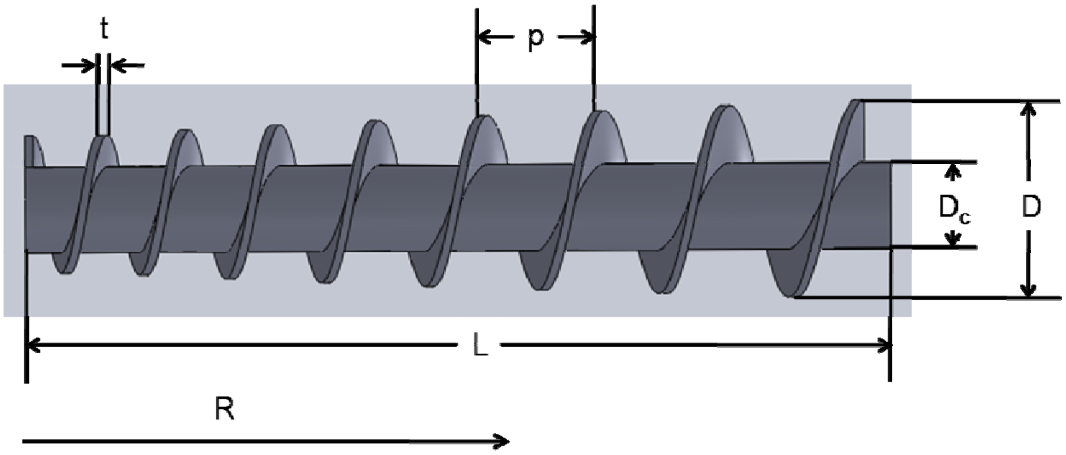


Figure 3. The schematic diagram of screw along radius direction in the pre-reduction shaft furnace model.

In Figure 3, the screw is along the radius direction, t, p, D_c, D and L represent tooth thickness, pitch, flight diameter, screw core diameter and screw length, respectively. In the present work, t, D_c and L are constants, which are 50 mm, 500 mm and 5,000 mm respectively. However, the flight diameter D and the pitch p are expanded along the screw length, which is shown in Table 1.

Table 1. Screw parameters used in the studied model

Number	0	1	2	3	4	5	6	7	8
D (mm)	800	800	850	900	950	1,000	1,050	1,100	1,150
p (mm)	400	450	500	550	600	650	700	750	800

Table 2. The parameters used in the simulation and the properties of particles and wall.

Parameter	Particle	Wall
Density	3450 (kg/m^3)	7850 (kg/m^3)
Shear modulus	2×10^{9} (Pa)	7.9×10^{10} (Pa)
Poisson's ratio	0.25	0.3
Static friction coefficient between particles (p-p)	0.5	-
Rolling friction coefficient between particles (p-p)	0.05	-
Restitution coefficient between particles (p-p)	0.5	-
Static friction coefficient of particle to wall (p-w)	-	0.5
Rolling friction coefficient of particle to wall (p-w)	-	0.05
Restitution coefficient of particle to wall (p-w)	-	0.4
Time step	1×10^{-5} (s)	

Since pellets are the main iron-bearing materials charged into the furnace, the balls are selected to simulate the pellets movement in this paper. The diameters of pellets have to be enlarged in order to shorten the simulation time for the large scaled model. The sizes of pellets are 100 mm, 200 mm and 300 mm. The initial partition of each kind of pellets is one third, and then they are mixed evenly before charged into the pre-reduction shaft furnace model. As the pellets are charged into the model uniformly, the eight screws start to rotate at a constant speed. If the rotary speed is the same as practical one, this simulation will spent much more time, so the rotary speed is also magnified to 20 radians per second. The material of pre-reduction shaft furnace and screw are assumed to be steel, The parameters used in the simulation and the properties of particles and wall are collected in Table 2.

3 RESULTS AND DISCUSSION

After simulating the pellets discharging from the pre-reduction shaft furnace model by screws, the descending velocity and the PSSB can be obtained. In order to investigate the characteristics of burden movements at different part and level, three layers, 2,4 and 6 m above the furnace bottom respectively, are selected to stand for the burden movement characteristics from bottom to top. And then 12 cylinders with 1 m heigh at each layer are selected to represent the burden movement behaviors at different layers inside the shaft furnace. The schematic diagram can be seen from Figure 4.

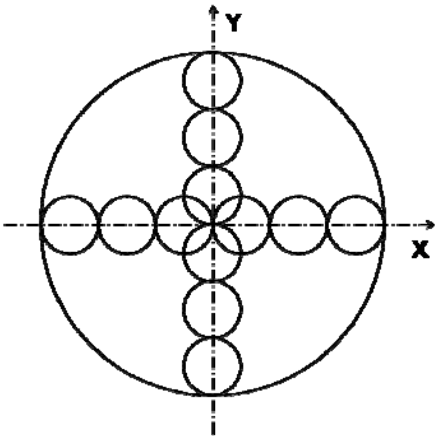


Figure 4. The schematic diagram of selecting cylinders at a layer.

In Figure 4, the four cylinders close to the centerline and the four cylinders near to the model edge of horizontal layer represent burden movement characteristics in central and peripheral areas of pre-reduction shaft furnace model. The rest four cylinders stand for the middle area. And the dimensionless radiuses of the central, middle, and edge are 1/6, 3/6 and 5/6 respectively. As for the three different areas, this paper simulates the burden descending velocity, which is simplified as the vertical component velocity because the horizontal component velocity is small enough to be neglected. Figure 5 demonstrates the vertical component velocity at three areas in the layer 2 m, 4 m and 6 m above the bottom.

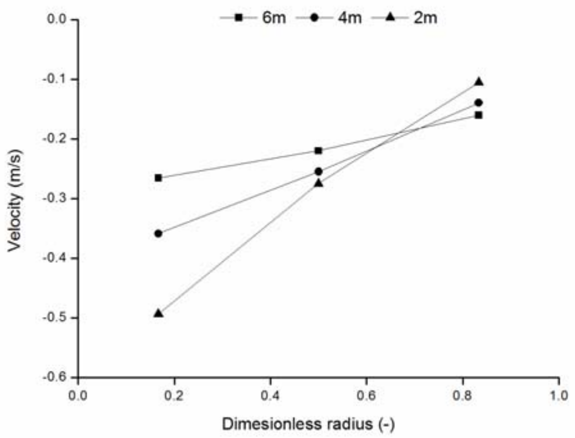


Figure 5. The burden descending velocity in pre-reduction shaft furnace model.

In Figure 5, the burden descending velocities in central and middle areas are becoming larger with the burden moving downward, especially in the central area, while that in edge area displays an opposite tendency. This is because that the carrying capability of the screw in central part is greater than that in middle or edge part. According to the DEM simulation, the PSSB can also be calculated with the results shown in Figure 6.

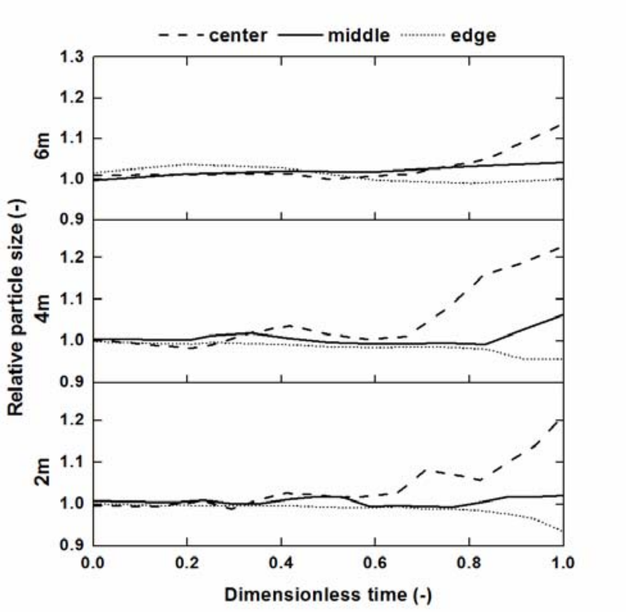


Figure 6. The relative particle size while discharging from the pre-reduction shaft furnace model.

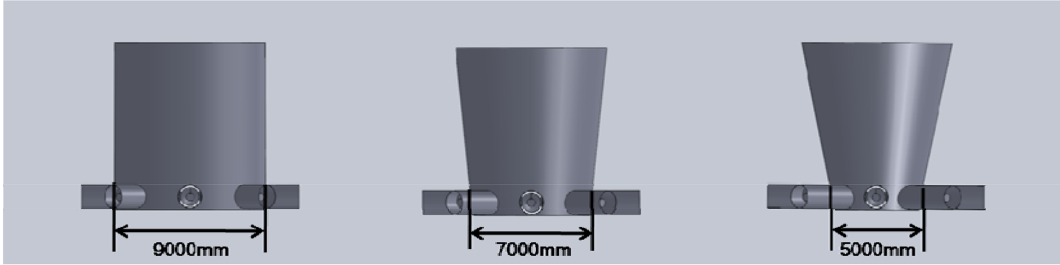
In Figure 6, the relative particle size (RPS), which simply sets the small, middle and large size pellets as dimensionless size 0.5,1 and 1.5, is used to demonstrate the PSSB while the burden discharging from the pre-reduction shaft furnace model. The discharging time starts to count when the screws starts working and ends when all the burdens have been drawn from each layer, so the discharging time of the layer 2m above the bottom is longer than that of the layer 4 m or 6 m above the bottom. In order to compare the RPS of different layers during discharging, the discharging times of three layers are normalized to dimensionless time shown in Figure 6. The RPS in central area stays about 1 before the dimensionless discharging time T=0.6 in different layers, and then increases greatly after T=0.6; the RPS in edge area also stay around 1 before T=0.8, and then decreases a little after T=0.8; while the RPS in middle area almost keeps about 1 during all the discharging process. This is because of the velocity distribution in different layers, the velocities reduces from center to edge area, which means that the burdens in central area move downwards more quickly than those in middle or edge areas. Thus the burdens have a move tendency from edge to center area as the large size particles are easier to roll than middle or small size particles, so the RPS in central area grows according to more quantities of large size particles flowing to this area, and RPS in edge area reduces for the same reason.

The research investigates the effects of pre-reduction shaft furnace bottom diameter, screw casing diameter, as well as screw rotating rate on burden descending velocity and PSSB, these factors and their values are shown in Table 3.

Table 3. The factors and their values investigated in this work.

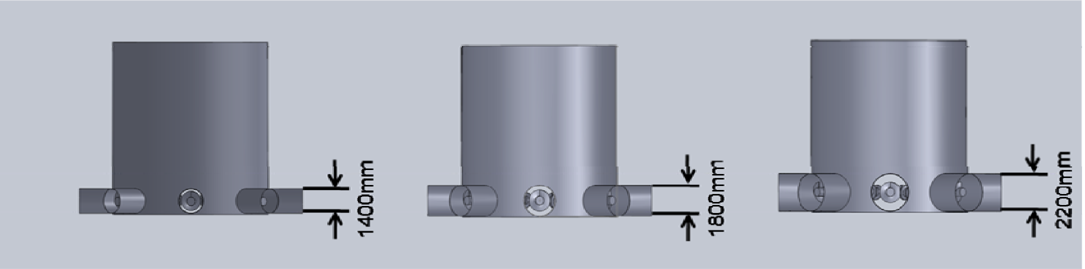
Factor	Value
Pre-reduction shaft furnace bottom diameter	5,000, 7,000 and 9,000 mm
Screw casing diameter	1,400, 1,800 and 2,200 mm
Screw rotating speed	10, 20 and 30 rad/s

The schematic diagrams of pre-reduction shaft furnace bottom diameter and screw casing diameters are shown in Figures 7 and 8.



(a) (b) (c)

Figure 7. The schematic diagrams of three kinds of pre-reduction shaft furnace bottom diameter. (a) 9,000 mm; (b) 7,000 mm; and (c) 5,000 mm.

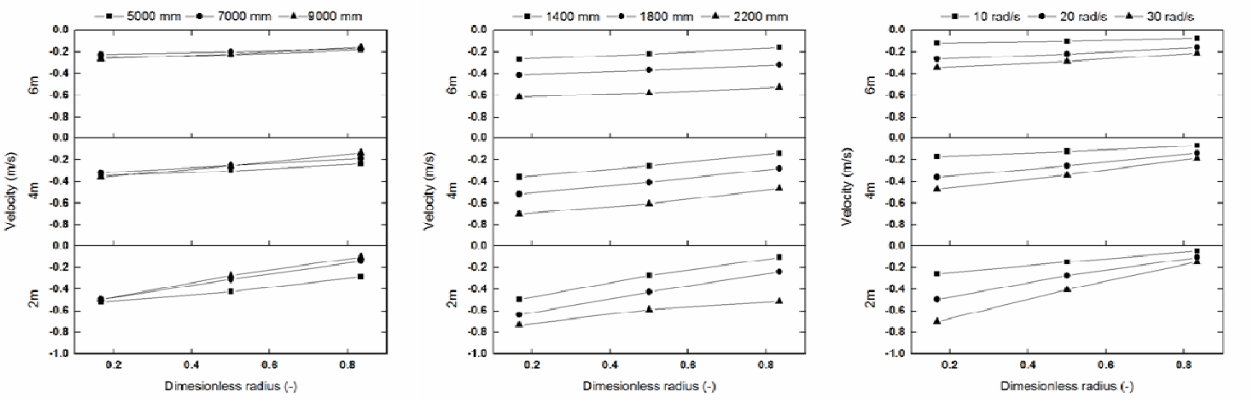


(a) (b) (c)

Figure 8. The schematic diagrams of three kinds of screw casing diameters. (a) 1,400 mm; (b) 1,800 mm; and (c) 2,200 mm.

3.1 Burden Descending Velocity

It is investigated that the effects of pre-reduction shaft furnace bottom diameter, screw casing diameter and screw rotating speed on the burden descending velocity distribution with the results shown in Figure 9.



(a) (b) (c)

Figure 9. The burden descending velocity distribution. (a) pre-reduction shaft furnace bottom diameter; (b) screw casing diameter; and (c) screw rotating speed.

The burden descending velocities at higher layer like 6m display few differences while they vary at lower layer like 2 m with the pre-reduction shaft furnace bottom diameter changing. The velocities increase greatly in the edge part with the pre-reduction shaft furnace diameter decreasing, however, they almost make no change in the central part. The burden velocities of 2,500 mm pre-reduction shaft furnace diameter are almost 3 times in the edge area than those in central area. The reason is that absolute positions of middle and edge area move towards the pre-reduction shaft furnace center with the diameter decreasing, thus the screw part corresponding to the middle and edge area can discharge more burdens relatively.

The burden velocities increase greatly with the screw casing diameter increasing in all three layers, and the increments grow gradually while the screw casing diameter increases, especially, the velocity in edge area of 2,200 mm casing diameter is 5 times as that of 1,400 mm casing diameter. By contrast, the velocity increment in edge area is greatest, the next is in middle area, and the smallest is in central area. The reason is that there will be more space for burden to discharge from the screw casing when the casing diameter grows.

Comparing with the base model whose rotating speed is 20 rad/s, the velocity decreases about 50% when the rotating speed is 10 rad/s while it increases about 30% when the rotating speed is 30 rad/s in each area, this means the burden descending velocities change synchronously at different area of different layer corresponding to the rotating speed.

3.2 Particle Size Segregation Behaviors

The effects of pre-reduction shaft furnace bottom diameter, screw casing diameter and screw rotating speed on the PSSB are also calculated with the results illustrated in Figures 10 to 12, respectively.

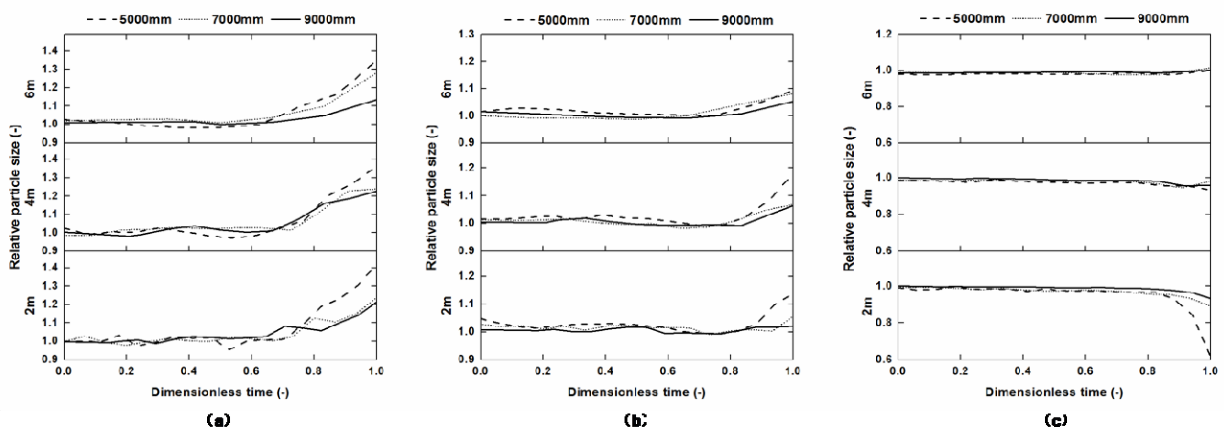
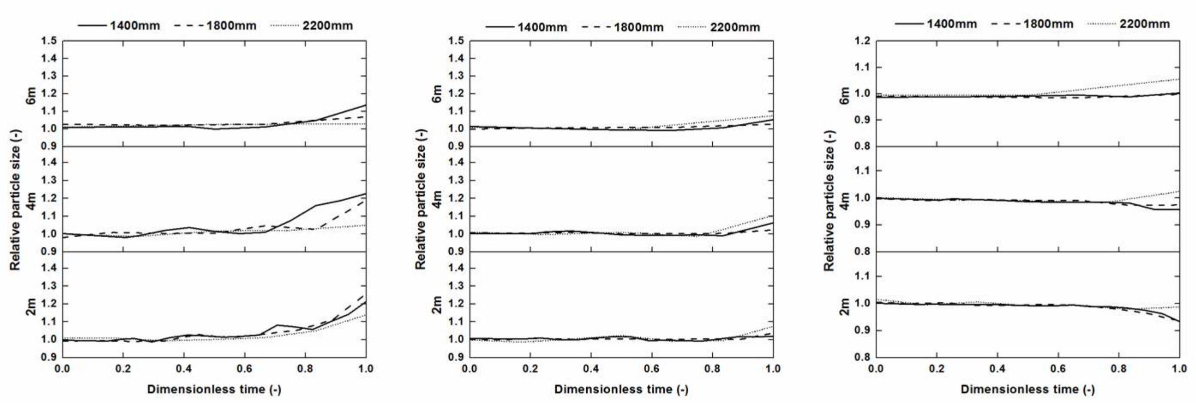


Figure 10. The relative particle size while discharging as function of pre-reduction shaft furnace bottom diameter. (a) central area; (b) middle area; and (c) edge area.

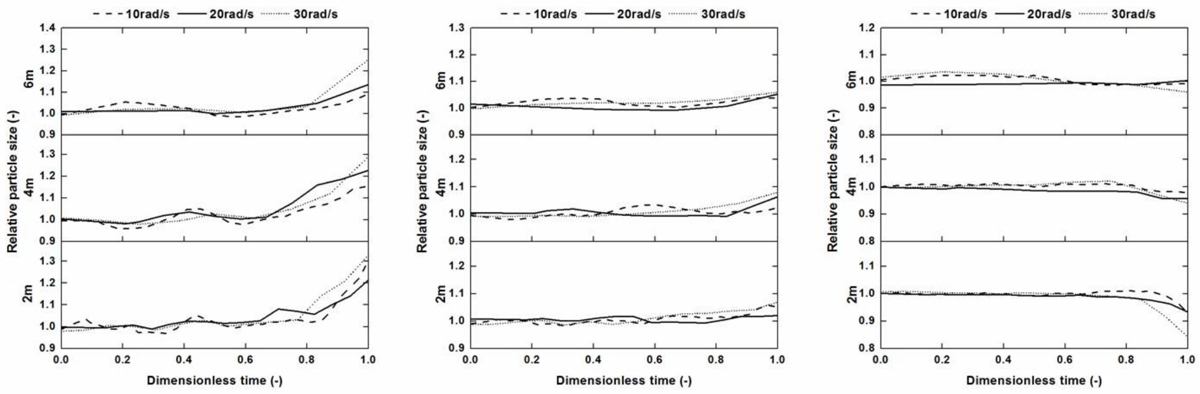
As for the particle movement in the central area shown in Figure 10a, the RPS almost remains unchanged before dimensionless discharging time T=0.6 for three layers, then the RPS turns larger later after T=0.6. This is because there will be a increasing horizontal component velocity with the decrease of furnace bottom diameter, thus the burden are more likely to roll towards from edge to center area, which results in the rise of the RPS in central area. As for the middle area in Figure 10b, the characteristics of RPS change is almost the same as that in central area, and the turning point time is T=0.8. As to the edge area, the RPS nearly keeps a constant at the layer of 4 m and 6m during the period of discharging, however, the RPS becomes smaller with the decrease of pre-reduction shaft furnace bottom diameter after the dimensionless discharging time T=0.8 at the 2 m layer. Specifically, the RPS is even 0.62 at the end of discharging in the 2 m layer at the case of 2,500 mm furnace bottom diameter. And the reason is the same as that in the central area. The results show that it is better to increase the pre-reduction shaft furnace bottom diameter so as to get a relatively uniform RPS distribution during discharging. The results also imply that the furnace shape has a greater effect on the PSSB than the vertical component velocity.



（a） （b） （c）

Figure 11. The relative particle size while discharging as function of screw casing diameter. (a) central area; (b) middle area; and (c) edge area.

In the central area shown in Figure 11a, the variation of RPS in cases of three different screw casing diameters exhibits almost the same tendency which changes little at first and then rises greatly during discharging. The RPS in the case of 2,200 mm screw casing diameter at the end of discharging is smallest in all layers among the three cases. The reason is that the burden descending velocity turns to more uniform in radius direction with the screw casing diameter increasing, which means the burden rolling tendency from edge to center areas become less obvious. In this way, the RPS of both middle and edge area in the case of 2,200 mm casing diameter turns to larger after the dimensionless discharging time T=0.8. Thus it can be concluded that the RPS tends to more uniform while discharging with the screw casing diameter increasing, so larger screw casing diameter is better for practical operation.



（a） （b） （c）

Figure 12. The relative particle size while discharging as function of screw rotating speed. (a) central area; (b) middle area; and (c) edge area.

As shown in Figure 12, the RPS changes little before the turning point time of T=0.7, and then increase greatly later in central area, furthermore the higher the rotating speed is, the larger the RPS will be at the end of discharging. On the contrary, the RPS reduces gradually after turning point time in edge area, and the RPS become smaller at the end of discharging when the screw rotating speed increases. The reason is that the velocity difference value along radius direction is more greater when the screw rotating speed is higher, which will result in the larger RPS in central area and smaller RPS in edge area at the end of discharging. So lower screw rotating speed helps to get a uniform RPS distribution during discharging, furthermore obtain a uniform gas distribution in furnace which is good for practical operation.

4 CONCLUSIONS

This work investigates the burden descending velocity and particle size segregation during discharging from the base model by DEM, and then the effects of pre-reduction shaft furnace bottom diameter, screw casing diameter as well as screw rotating speed on burden descending and particle size segregation behaviors are studied. The summaries are as follows.

- The burden descending velocities turn to larger in central and middle area while get smaller in edge area from top to bottom when the burdens are discharging from the pre-reduction shaft furnace. The particle size segregates little in all areas within the dimensionless discharging time T=0.6, the relative particle size increases significantly in the central area and decreases a little in the edge area after T=0.6.
- To reduce the pre-reduction shaft furnace bottom diameter increases the burden velocities most in edge area, a little in middle area while almost makes no difference on the central area. To increase the screw casing diameter and the screw rotating speed increase the burden velocities in all areas. The increment is biggest in the edge area, smallest in the central area in the case of screw casing diameter, and it almost keep the same amplitude in all areas in the case of screw rotating diameter.
- In order to gain a relatively uniform RPS distribution during discharging, it is recommended to increase the pre-reduction shaft furnace bottom diameter and to enlarge the screw casing diameter, or to decrease the screw rotating speed.

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