1. Introduction

Recently, low reducing agent operation of the blast furnace has attracted much attention in the ironmaking process owing to the phenomenon of global warming. With the decrease of the coke ratio, the stable operation of the blast furnace becomes very important. The blast furnace is a countercurrent reactor involving the complex heat transfer, mass transfer, momentum transfer, and chemical reactions between ascending gas and descending solid particles. It is one of the most important factors for stable operation of the blast furnace to optimize the burden distribution. Because the efficiency of smelting is dominated by the gas distribution. Then the processes of coke charging into and discharging from the left hopper and right hopper were calculated by the discrete element method (DEM) model, respectively. The calculation results show that the burden distribution of the left hopper and right hopper was not symmetric, which caused the asymmetric and uneven distribution of coke in the radial and circumferential direction of stock surface, respectively. In the case of coke was discharged from the left hopper, the total volume of coke in the radial region 1 to 9 was smaller than that in the radial region 12 to 20 of stock surface. And the total volume of coke in the circumferential region 1 to 4 was larger than that in the circumferential region 5 to 8 of stock surface. However, the burden distribution of stock surface was contrary when coke was discharged from the right hopper.

KEY WORDS: main feeding belt; bell-less top; blast furnace; two parallel hoppers; DEM.

Effect of the Main Feeding Belt Position on Burden Distribution during the Charging Process of Bell-less Top Blast Furnace with Two Parallel Hoppers

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Based on an actual 4 070 m$^3$ bell-less top blast furnace with two parallel hoppers in China, a full model of bell-less top mainly consisting of a bunker, a main feeding belt, a switch chute, two parallel hoppers, a central throat tube, a rotating chute and a throat of blast furnace was established in this study. Specifically, the angle between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers is 22 degrees. Then the processes of coke charging into and discharging from the left hopper and right hopper were calculated by the discrete element method (DEM) model, respectively. The calculation results show that the burden distribution of the left hopper and right hopper was not symmetric, which caused the asymmetric and uneven distribution of coke in the radial and circumferential direction of stock surface, respectively. In the case of coke was discharged from the left hopper, the total volume of coke in the radial region 1 to 9 was smaller than that in the radial region 12 to 20 of stock surface. And the total volume of coke in the circumferential region 1 to 4 was larger than that in the circumferential region 5 to 8 of stock surface. However, the burden distribution of stock surface was contrary when coke was discharged from the right hopper.

KEY WORDS: main feeding belt; bell-less top; blast furnace; two parallel hoppers; DEM.
in the lower part of the hopper. Mio et al. established a full model of the charging process in the bell-less top blast furnace and analyzed the particle segregation in spatially-distributed and temporally-distributed in each process. The study showed that the larger particles tend to be discharged last, because they are near the side wall in the surge hopper or the parallel ones. Ketterhagen et al. studied the particle flow mode with hopper and delineated the mass-flow and funnel-flow behavior based on the hopper wall angle. In addition, the author proposed a Mass Flow Index (MFI) to quantitatively characterize the nature of the flow pattern as a mass-flow, funnel-flow, or some intermediate.

When the bell-less top system is equipped with serial hoppers, the influence of the relative position between the centerline of the main feeding belt and the serial hoppers is negligible. However, the relative position between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers is crucial when the bell-less top system is equipped with two parallel hoppers. In some iron and steel enterprises of China, the centerline of the main feeding belt doesn’t coincide with the symmetry plane of two parallel hoppers, leading to many difficulties in the operation of blast furnace. However, scholars at home and abroad have few studies on it. Therefore, in this study, the full model of the 4070 m³ blast furnace with two parallel hoppers was established, which mainly includes a bunker, a main feeding belt, a switch chute, two parallel hoppers, a center throat tube, a rotate chute and a throat. Specifically, the angle between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers is 22 degrees, as shown in Fig. 2.

2.2. Physical Model

Based on the actual 4070 m³ blast furnace in China, the physical model of charging system of bell-less top blast furnace with two parallel hoppers was established, which mainly includes a bunker, a main feeding belt, a switch chute, two parallel hoppers, a center throat tube, a rotate chute and a throat. Specifically, the angle between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers is 22 degrees, as shown in Fig. 2.

2.3. Calculation Conditions

In this study, the processes of coke charging into and discharging from the left hopper and right hopper were calculated, respectively. In the charging process, the coke is generated in the bunker initially, and then it is charged into the left hopper or right hopper via the main feeding belt and switch chute. After the completion of coke charging into the left hopper or right hopper, the gate of hopper rotates a constant angle immediately, so the mass flow rate of coke through the gate is almost keep constant. Finally, the coke is charged into the stock surface via the rotate chute. The rotational speed of the rotating chute is 8 rpm in the calcu-

\[
m_i \frac{d \mathbf{u}_i}{dt} = \sum_{j=1}^{N} \left( F_{n,ij} + F_{d,ij} + F_{c,ij} + F_{r,ij} \right) + m_i \mathbf{g} \quad \ldots \ldots \ldots \ldots \ldots (1)
\]

\[
I_i \frac{d \omega_i}{dt} = \sum_{j=1}^{N} \left( T_{n,ij} + T_{r,ij} \right) \quad \ldots \ldots \ldots \ldots \ldots (2)
\]

Where \( m_i, \mathbf{u}_i, \omega_i, \mathbf{I}_i \) are the mass, velocity, angular velocity, the moment of inertia of particle \( i \), respectively; \( \mathbf{g} \) is the acceleration of gravity; \( F_{c,ij}, F_{d,ij}, F_{r,ij} \) is the normal contact force, normal damping force, tangential contact force, tangential damping force, respectively; The torque acting on particle \( i \) includes a component from tangential force, \( T_{r,ij} \) and another from the rolling friction, \( T_{n,ij} \); \( N \) is total number of other particles contact with particle \( i \).

### Table 1. The size distribution of coke in the present calculation.

| Diameter (mm) | Mass (kg) | Mass fraction (%) | Total number (-) |
|--------------|-----------|------------------|------------------|
| >120         | 58        | 0.25             | 64               |
| 90–120       | 4441      | 19.31            | 7327             |
| 60–90        | 11040     | 48               | 49979            |
| 37.5–60      | 6888      | 29.95            | 113554           |
| <37.5        | 573       | 2.49             | 20741            |
| Sum          | 23000     | 100.00           | 191665           |
lation process, and the rotational direction of the rotating chute is clockwise in the top view. It is assumed that the initial stock surface is a horizontal plane as it is difficult to determine the shape of stock surface. In addition, the stock line is 1.4 m in the calculation process. In order to mitigate the calculation load, the coke diameter has been magnified 1.5 times for reducing the particle number. The size distribution of coke in the present calculation is showed in Table 1, and the physical parameters of materials in this study are presented in Table 2.22,23)

3. Results and Discussion

3.1. The Motion Behaviors of Particles in the Switch Chute

To investigate the effects of the main feeding belt position on the motion behavior of particles during the charging process, the analysis zone at the outlet of the switch chute is used to monitor the variation of coke average velocity. The variation of coke average velocity during coke charging into different hoppers is showed in Fig. 3. It is can be obtained that the average velocity of coke is larger while coke is charging into the right hopper compared to coke is charging into the left hopper. The reason is that the motion direction of particles is near the right hopper before particles collide with the switch chute, which is not along the gravity direction. Therefore, the loss of kinetic energy after particles collide with the switch chute is larger while coke is charging into the right hopper, resulting in the average velocity of coke at the outlet of the switch chute is smaller.

3.2. Burden Distribution in the Radial Direction of Two Parallel Hoppers

During the process of hopper charging, the position of the burden apex moves toward to the centerline of blast furnace gradually, the cross-section color mapping of charged time of coke is showed in Fig. 4. The particles, which are colored by the charging time, are charged into the hopper. After coke is charged into the left hopper and right hopper completely, the distance between the burden apex and the inside wall of the hopper is 2 200 mm in the left hopper, but 2 400 mm in the right hopper, because the velocity of coke at the outlet of the switch chute is larger while coke is charging into the right hopper, as shown in Fig. 3.

In order to investigate the burden distribution in two parallel hoppers, the left hopper and right hopper are divided into ten regions by equal-area along the x axis direction and

Table 2. The physical parameters of materials in the present calculation.22,23)

| Item       | Density (kg m\(^{-3}\)) | Shear modulus (Pa) | Poisson ratio (−) | Coefficient of restitution (−) | Coefficient of static friction (−) | Coefficient of rolling friction (−) |
|------------|-------------------------|--------------------|-------------------|-------------------------------|-----------------------------------|-----------------------------------|
| Coke       | 1 050                   | 2.2×10\(^7\)       | 0.22              | −                             | −                                 | −                                 |
| Wall       | 4 500                   | 5.0×10\(^9\)       | 0.30              | −                             | −                                 | −                                 |
| Belt       | 1 200                   | 1.0×10\(^7\)       | 0.40              | −                             | −                                 | −                                 |
| Coke-Coke  | −                       | −                  | −                 | 0.18                          | 0.56                              | 0.15                              |
| Coke-Wall  | −                       | −                  | −                 | 0.20                          | 0.41                              | 0.09                              |
| Coke-Belt  | −                       | −                  | −                 | 0.10                          | 0.90                              | 0.34                              |

Fig. 3. Variation of coke average velocity in the analysis zone during coke charging into different hoppers. (Online version in color.)

Fig. 4. The cross-section color mapping of charged time of coke (a) left hopper; (b) right Hopper. (Online version in color.)
the y axis direction, respectively, as shown in Fig. 5. Owing to the area of each region is equal, the total volume of coke in each region represents the height of the burden layer in a way. Along the x axis direction or y axis direction, the total volume distribution of coke in the left hopper and right hopper is not symmetric, as shown in Fig. 6. Additionally, along the x axis direction of the hopper, the total volume of particles from the region 1 to 5 of the left hopper is higher than that in the corresponding region of the right hopper. However, the total volume of particles from the region 6 to 10 of the left hopper is lower than that in the corresponding region of the right hopper. Along the y axis direction of the hopper, the total volume of particles from the region 1 to 5 of the left hopper is lower than that in the corresponding region of the right hopper. But the total volume of particles from the region 6 to 10 of the left hopper is higher than that in the corresponding region of the right hopper. The reason is that the total volume of particles in each region is determined by the position of burden apex in the left hopper and right hopper.

3.3. Burden Distribution in the Circumferential Direction of Two Parallel Hoppers

Similarly, the left hopper and right hopper are divided into eight regions by equal-area in the circumferential direction, as shown in Fig. 7. Figure 8 shows the total volume distribution of coke in the circumferential direction of two parallel hoppers. The total volume distribution of coke in the circumferential direction of the left hopper is more uniform.
than that in the right hopper, and the standard deviation of the coke total volume distribution in the circumferential direction of the left hopper and right hopper is 0.065 and 0.261, respectively. The reason is also that the heap apex position of coke in left hopper and right hopper is different, owing to the coke average velocity at the outlet of the switch chute is different, as discussed in the part 3.1.

### 3.4. Burden Distribution in the Radial Direction of Stock Surface

Figure 9 shows the cross-section color mapping of discharged time of coke. It can be obtained that the particles located at the top of the hopper outlet flow out firstly, but the particles located on the outside wall of the hopper flow out last. It should be pointed out that the flow pattern of particles depends on the structure of the hopper.

Variation of particle size in the charging process has great effects on the coke size distribution in the radial direction of stock surface. Therefore, analysis zone in the outlet of the hopper is used to monitor the variation of coke average diameter in the charging process, as shown in Fig. 10. During the early 60 s of the charging process, the coke average diameter almost keeps stable. Then the coke average diameter increases gradually until the charging time reach to 120 s approximately. Finally, the coke average diameter decreases sharply, as many small particles stay on the wall of the hopper.

In order to investigate the burden distribution in the radial direction of stock surface, twenty regions were divided by equal-area along the x axis direction and y axis direction, respectively. Schematic of the regional division of stock surface in the radial direction is showed in Fig. 11. And the cross-section snapshot of burden distribution on the stock surface in different circumferential direction is shown in Fig. 12. It is obviously seen that burden distribution in the radial direction of stock surface is not symmetric, and the burden distribution in the circumferential direction of stock surface is not uniform. The details of burden total volume

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**Figure 9.** The cross-section color mapping of discharged time of coke (a) left hopper; (b) right hopper. (Online version in color.)

**Figure 10.** Changes in average diameter of coke discharged from the hopper over time. (Online version in color.)
distribution and burden average diameter distribution are analyzed as follow.

**Figure 13** shows the total volume distribution of coke in the radial direction of stock surface. The charging matrix of coke in the calculation is \( C_{30.5}^{1} 38.5^{3} 36.5^{3} 34.5^{2} 32.5^{2} 30.5^{2} 28.5^{2} \), and the initial stock surface is assumed as a plane. Owing to the minimum angle of chute tilting is 28.5 degrees, the total volume of particles in the region 10 and 11 is almost zero. Along the x axis direction of stock surface, the total volume distribution of coke is not symmetric with the centerline of blast furnace whether coke is discharged from the left hopper or right hopper. When the coke is discharged from the left hopper, the total volume of particles from the region 1 to 10 of stock surface is lower than that in the right hopper. On the contrary, from the region 11 to 20 of stock surface, the total volume of particles in each region is higher than the right hopper while coke is discharged from the left hopper. Therefore, it can be concluded that changing the charging pattern of each batch can decrease the segregation of burden volume distribution in the radial direction of stock surface. However, an interesting phenomenon should be pointed out that the total volume distribution of coke along the y axis direction of stock surface is symmetric with the centerline of blast furnace whether coke is discharged from the left hopper or right hopper. The reason is that the effective motion length of coke on the rotating chute is same when the rotating chute rotates through the positive and negative y axis, respectively. Therefore, the velocity of coke at the outlet of the rotating chute is same, then the total volume distribution of coke along the y axis direction is similar. On the contrary, the effective motion length of coke on the rotating chute is not same when the rotating chute rotates through the positive and negative x axis, respectively. Therefore, the velocity of coke at the outlet of the rotating chute is different, then the total volume distribution of coke along the x axis direction is not symmetric.

**Figure 14** shows the average diameter distribution of coke in the radial direction of stock surface. Along the x axis direction and the y axis direction of stock surface, it can be obtained that the coarse particles stay in the center and edge of stock surface easily, but the fine particles tend to gather in the heap apex. And the average diameter distribution of coke along the x and y axis direction is similar whether coke is charged from the left hopper or right hopper. The reason is that the average diameter distribution of coke is mainly depended on the heap apex and valley position of burden,

![Figure 13](image1.png)

*Fig. 13. The total volume distribution of coke in the radial direction of stock surface (a) along the x axis; (b) along the y axis. (Online version in color.)*

![Figure 14](image2.png)

*Fig. 14. The average diameter distribution of coke in the radial direction of stock surface (a) along the x axis; (b) along the y axis. (Online version in color.)*
however, the heap apex and valley position along the x and y axis direction is almost same whether coke is discharging from the left hopper or right hopper, as shown in Fig. 13. It is can be concluded that the main feeding belt position mainly affects the burden total volume distribution of stock surface, but the effects of the main feeding belt position on the heap apex position of burden is negligible. In other words, the effects of the main feeding belt position on the coke average diameter distribution on the stock surface is insignificant.

3.5. Burden Distribution in the Circumferential Direction of Stock Surface

Similarly, in the circumferential direction of stock surface, which is divided by eight equal-area parts, as shown in Fig. 15. Figure 16 shows the coke total volume distribution in each region of stock surface. In the case of coke is charged into the stock surface from the left hopper, the total volume of particles from the region 1 to 6 is larger than that in the corresponding region of the right hopper. On the contrary, the total volume of particles from the region 7 to 12 is smaller than that in the corresponding region of the right hopper. When the coke is charged into the stock surface from the left hopper and right hopper, respectively, the standard deviation of the coke total volume distribution in the circumferential direction of stock surface is 0.075 and 0.074. The reason is that the effective motion length of coke on the rotating chute is different at the same circumferential angle of the chute while coke is charged from different hoppers. Consequently, the mass flow rate of coke is different at the same circumferential angle of the chute, this phenomenon can be explained in previous study. In addition, it is also obtained that the segregation of burden volume distribution in the circumferential direction of stock surface can be decreased by changing the charging pattern of each batch.

In the case of coke is discharged from the left hopper, the average diameter distribution of coke likes a V shape in the circumferential direction of stock surface, as shown in Fig. 17. On the contrary, in the case of the coke is discharged from the right hopper, the average diameter distribution of coke likes an inverse-V shape in the circumferential direction of stock surface. As discussed in the previous part-3.4, the average diameter distribution of coke is depended on the total volume distribution of coke in the circumferential direction of stock surface. However, the total volume distribution in the circumferential direction is uniform than that in the radial direction. Therefore, the difference between the maximum and minimum of the coke average diameter is only 2 mm approximately.

4. Conclusions

Based on an actual 4 070 m$^3$ bell-less top blast furnace with two parallel hoppers in China, the influence of the angle between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers with 22 degrees on burden distribution of two parallel hoppers and stock surface was investigated by discrete element method. Some conclusions are as follows:

(1) In the radial direction of two parallel hoppers, the distance between the burden apex and the inside wall of the hopper is 2 200 mm in the left hopper, but 2 400 mm in the right hopper, respectively, as the angle between the main feeding belt centerline and the symmetry plane of two parallel hoppers is 22 degrees. In the circumferential direction of the hopper, the standard deviation of the coke total volume distribution in the circumferential direction of stock surface is 0.075 and 0.074. The reason is that the effective motion length of coke on the rotating chute is different at the same circumferential angle of the chute while coke is charged from different hoppers. Consequently, the mass flow rate of coke is different at the same circumferential angle of the chute, this phenomenon can be explained in previous study. In addition, it is also obtained that the segregation of burden volume distribution in the circumferential direction of stock surface can be decreased by changing the charging pattern of each batch.

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(1) In the radial direction of two parallel hoppers, the distance between the burden apex and the inside wall of the hopper is 2 200 mm in the left hopper, but 2 400 mm in the right hopper, respectively, as the angle between the main feeding belt centerline and the symmetry plane of two parallel hoppers is 22 degrees. In the circumferential direction of the hopper, the standard deviation of the coke total volume distribution in the circumferential direction of stock surface is 0.075 and 0.074. The reason is that the effective motion length of coke on the rotating chute is different at the same circumferential angle of the chute while coke is charged from different hoppers. Consequently, the mass flow rate of coke is different at the same circumferential angle of the chute, this phenomenon can be explained in previous study. In addition, it is also obtained that the segregation of burden volume distribution in the circumferential direction of stock surface can be decreased by changing the charging pattern of each batch.

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distribution of the left hopper and right hopper is 0.065 and 0.261, respectively.

(2) Along the x axis direction of stock surface, whether coke is discharged from the left hopper or right hopper, the total volume distribution of coke is not symmetric with the centerline of blast furnace. However, the total volume distribution of coke is symmetric with the centerline of blast furnace along the y axis direction of stock surface. In the circumferential direction of stock surface, when coke is discharged from the left hopper and right hopper completely, the standard deviation of coke total volume in the circumferential direction of stock surface is 0.075 and 0.074, respectively.

(3) Because the bell-less top system with two parallel hoppers will cause the segregation of burden distribution on stock surface, the centerline of the main feeding belt will not coincide with the symmetry plane of two parallel hoppers, leading to the segregation of burden distribution on stock surface worse. It is concluded that the segregation of burden distribution can be reduced by changing the charging pattern of each batch or adjusting the structure of the switch chute when the centerline of the main feeding belt and the symmetry plane of two parallel hoppers is not coincident. In addition, the influence of the angle magnitudes between the centerline of the main feeding belt and the symmetry plane of two parallel hoppers on burden distribution will be investigated in the future.

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