Numerical Investigation of Coke Collapse and Size Segregation in the Bell-less Top Blast Furnace

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The coke collapse phenomenon significantly affects the burden and gas distributions, and further gas utilization and CO₂ emission. Therefore, it is necessary to investigate the coke collapse in blast furnace. A three dimensional model of bell-less top blast furnace is established based on discrete element method (DEM). The effects of chute angle, rotating speed and sinter amount on the coke collapse characteristics are then investigated based on this model. The results show that coke profile changes a lot after its collapse and the collapse region is more than 40% of the furnace radius. Sinter amount affects the coke collapse amount much, followed by chute angle and chute rotating speed. The coke collapse region is affected most by sinter amount, followed by chute rotating speed and chute angle. Large chute angle, higher rotating speed and small sinter amount are recommended for practical operation since they help to obtain a lighter coke size segregation along radius.

KEY WORDS: blast furnace; coke collapse; DEM; size segregation.

1. Introduction

Ore and coke are charged into blast furnace top alternately, so burdens display a layered structure in lump ore zone. Coke layer collapses when ore is dumped onto the coke surface because of ore’s large momentum. This leads to the change of burden distribution, and the radial ore to coke ratio is also different from the desired design. As a result, the burden permeability and gas distribution are then affected and further the gas utilization. The coke collapse phenomenon is inevitable in blast furnace. Therefore, the coke collapse is significantly important to the burden and gas distribution, and further affects the gas utilization and CO₂ emission.1,2)

Hockings et al. found that the coke surface profile changed much and the radial burden distribution is significantly affected by coke collapse with 1:1 scaled cold model.1) Okuno et al. investigated the effect of inclination angle of coke layer on the coke collapse magnitude with a reduced-size experimental apparatus and developed a mathematical model for quantitative evaluation of coke collapse by introducing the theory of soil mechanics.3) Jimenez et al. reappeared the evolution of coke layer by digital image processing with a 1/10 scale half-section cold model.4) However, the burden layer may be disturbed or the results may induce wall effects in the above experiments. Therefore, mathematical models are introduced to analyze coke collapse. Inada et al., Kajiwara et al., Radhakrishnan and Ram developed mathematical models to investigate coke collapse phenomenon based on the formation energy of mixed layer.5,6) Okuno et al., Nag et al., Wu et al., used the theory of soil mechanics to study the coke layer stability.3,7,8) Recently, discrete element method (DEM), developed by Cundall and Strack, has become one of the most popular and reliable simulation methods for granular behavior.9) It has been widely applied in ironmaking field, especially the burden distribution in blast furnace. Mitra and Saxén introduced DEM to simulate the burden formation of coke and ore layers and found that DEM simulation gave a better understanding of coke collapse at different charging program. This confirms that DEM is a feasible and reasonable way to investigate the coke collapse.10)

Therefore, in the present work, a three dimensional model of blast furnace top is established based on DEM. Then this model is used to investigate the effects of rotating chute angle, rotating speed and the amount of sinters on the coke collapse and corresponding size segregation.

2. Model Establishment

2.1. DEM Model

In DEM, particles’ movements are described as inter-particle contact model that a particle may collide with neighboring particles or the wall.5,11) This model consists of spring and dashpot in the normal direction, spring, dashpot and slider in the tangential direction, respectively.

At any time , the governing equations for particle can

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be written as follows: 12–14)

\[
\frac{dN_i}{dt} = \sum_{j=1}^{K} (F_{m,ij} + F_{b,ij} + F_{d,ij} + F_{d,ij}) + m_i g \quad \cdots \cdots \cdots (1)
\]

\[
I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{K} (M_{i,ij} + M_{d,ij}) \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots 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3. Results and Discussion

3.1. Base Model

Since coke collapses under the effect of ore hitting, some cokes will run away from their original place, which results in the change of radial coke amount. The radial coke change amount can be obtained as follows. Firstly, ten concentric cylinders with the burden profile height are adopted to extract the burden distribution data, and their radiiuses are 0.1R, 0.2R, 0.3R… and to 1.0R, respectively. Secondly, the masses of cokes in ten cylinders can be extracted. Thirdly, the masses of cokes in cylinder with the radius of 1.0R minus those in cylinder with the radius of 0.9R is the masses of cokes in the outer annular solid, which can be used to represent the coke amount at 0.95R. The masses of cokes in other nine annular solids can be calculated in the same way. At last, the increase of coke amount can be calculated by subtracting the initial coke amount in radial direction with the coke amount after collapse.

Figure 2 presents the increase of coke amount in radial direction in base model after three rings charging, where the negative value indicates that coke run away from this position and coke collapse takes place.

It can be seen from Fig. 2 that the increase of coke amount is positive within 0.4R and beyond 0.8R which suggests cokes tend to move to these areas, while it is negative between 0.4R and 0.8R which suggests cokes leave and run away from these areas. It can be inferred that the area between 0.4R and 0.8R is the place where coke collapse happened. However, the position is not accurate enough. Therefore, the method of image processing is applied to obtain the specific coke collapse position.

A slice, perpendicular to the horizontal plane and through the centerline of blast furnace, with thickness of 0.2 m is extracted before and after the coke collapse, shown in Figs. 3(a) and 3(b), where yellow, black and green particles represent sinter base, coke and charged sinter, respectively. The burden profiles are simplified as irregular curves based on the simulated results, shown in Fig. 3(c), where blue and red lines represent coke profiles before and after collapse. It can be seen that the coke profile changes significantly after ore’s charging.

It can be also found that there is a cross point near furnace center between the blue and red lines. Within this cross point, cokes move towards furnace center while cokes collapse or are squeezed away from their original positions beyond the cross point. This position stands for the ending position of the coke collapse. It can be also found that the red line and the blue line almost overlap towards wall direction. The beginning position of the overlap represents the starting position of the coke collapse. The region between the starting position and the ending position of the collapse is where the coke collapse takes place, which is defined as the “coke collapse region”. Coke collapse amount in this work is the weight of cokes which collapse or move away from their original positions under the strike and pressure from ores. Therefore, the coke collapse amount can be calculated by subtracting the original coke amount before collapse with the coke amount after collapse in the coke collapse region.

After extracting the coke profiles at different directions (±X and ±Y) and determining the starting and ending positions of coke collapse, the average positions are calculated. The coke amount is extracted in the coke collapse region and coke collapse amount is then calculated. The coke collapse region is from 1.96 m to 4.05 m, and the span is calculated as 2.09 m, which accounts for 41.3% of the furnace radius. The coke collapse amount in the base case model is 940.0 kg.

The collapse region is then divided into four equal rings along radial direction. The coke amounts of different sizes can be extracted before and after coke collapse. The segregation index is introduced to evaluate the burden size segregation as the result of coke collapse, which can be calculated by subtracting the initial coke amount in radial direction with the coke amount after collapse in the coke collapse region.

![Fig. 2. The increase of coke amount in radial direction.](image)

![Fig. 3. Burden profiles in the simulation of base model (a) before collapse; (b) after collapse; (c) coke collapse line. (Online version in color.)](image)
calculated by Eq. (3).

$$\text{SI}_k = \frac{\text{MFA}_k - \text{MFB}_k}{\text{MFB}_k} \quad \ldots (3)$$

Where, \(MFA\) and \(MFB\) represent the mass fractions of each size coke after and before coke collapse. The subscript \(k\) means different sizes of coke, in detail, \(L\), \(M\) and \(S\) stands for large, medium and small size cokes, respectively. If \(SI\) is negative, it means that this kind of particle collapses more than its original mass fraction before collapse, and vice versa. It should be noticed that the amount of this kind of particle is still less than the mass fraction before collapse no matter \(SI\) of this particle is negative or not, as long as this kind of particle belongs to the collapse region.

It can be from Fig. 4 that \(SI_L\) and \(SI_M\) are almost negative while \(SI_S\) is positive along radial direction in collapse region. The absolute values of \(SI\) almost decrease along radial direction. This suggests that different sizes cokes collapse more close to center (near collapse ending position) and less close to wall (near collapse starting position). The reason is that cokes tend to roll to the center since cokes form a funnel in the furnace. Cokes near collapse ending position receive more impacts from cokes that rolling from the collapse starting position. This also indicated that large and medium size cokes collapse more than small size cokes. The reason is that large and medium size cokes have larger rollability and momentum than small size cokes.

3.2. Chute Angle

The coke collapse amounts are 532.1 kg, 940.0 kg and 576.9 kg for 25°, 30° and 35° chute angles, respectively. It can be found that coke collapse amounts increase and reaches maximum at 30° chute angle, and then decreases when the chute angle increases. This indicates that there is a critical chute angle when the cokes have the largest collapse amount. And the burden striking point may be right on the turning point of funnel and platform of coke profile where cokes are not stable enough. However, when the sinter amount is 5 rings weighted, the conclusion is changed. The coke collapse amounts are 625.7 kg, 1 479.2 kg and 1 501.9 kg for 25°, 30° and 35° chute angles, respectively.

It can be found that the coke amount is the largest for 35° chute angle. The reason is that more sinters stay on the coke platform, which leads to the collapse of coke platform. It can be also found that the coke collapse amount increase little for 25° chute angle. This is because that coke collapses in a narrow region, only on the coke funnel, and the room becomes limited since more cokes are accumulated in the center. Therefore, the chute angle should be smaller than the critical value when the sinter amount is large.

Figure 5 presents the collapse starting and ending positions, and collapse region span at different chute angles. It can be seen from Fig. 5 that the collapse starting and ending position increase with the increase of chute angle. This implies that the collapse region move towards wall direction when the chute angle increases. The reason is that the striking of sinter on coke surface is the cause of coke collapse and the striking point of sinter moves towards the wall direction with the increase of chute angle. The collapse region spans are 2.00 m, 2.09 m and 1.89 m for 25°, 30° and 35° chute angles, respectively. This indicates that the coke is not easy to collapse at 25° and 35° chute angle relatively. The reason is the same as that for the coke collapse amount.

Figure 6 shows the \(SI\) for different size cokes in collapse region at different chute angles. It can be seen from Fig. 6 that the \(SI\) of different size cokes have the similar tendency along radial direction at different chute angles. It should be noticed that the absolute values of different size cokes’ \(SI\) are large in first half of collapse region while small in the other half of collapse region at 25° chute angle. This indicates that coke collapse segregates more close to the center. The absolute values of different size cokes’ \(SI\) are relative small and decrease gradually along radius at 35° chute angle. This implies that coke collapses relatively uniform along radius. Therefore, the chute angle should be larger than the critical value in the case of less ore charging due to small collapse amount and relatively uniform collapse along radius while it should be smaller than the critical value in the case of large amount of ore charging due to small collapse amount.
3.3. Rotating Speed

The largest rotating speed in this work is set as 72°/s since too large rotating speed is not realistic for practical operation. Therefore, the sinter amount is set as 17 200 kg in this section. In this way, the chute rotates just 1 ring for 24°/s, 2 rings for 48°/s and 3 rings for 72°/s rotating speed. This is more accurate and better to extract the coke collapse profile and size distribution along radial direction.

The coke collapse amounts are 588.8 kg, 547.8 kg and 357.9 kg for the rotating speeds of 24°/s, 48°/s and 72°/s, respectively. It can be found that the coke collapse amount decreases with the increase of rotating speed. The reason is that the velocity component in tangential direction increases with the increase of rotating speed, which leads cokes to collapse more in tangential direction than in radial direction. However, cokes in tangential direction are not easy to collapse comparing with those in radial direction. Therefore, it

Fig. 6. $SI$ of different size cokes in collapse region along radial direction at different chute angles (a) 25°, (b) 30° and (c) 35°.

Fig. 7. The collapse starting and ending positions and collapse region span at different rotating speeds.

Fig. 8. $SI$ of different size cokes in collapse region along radial direction at different rotating speeds (a) 24°/s, (b) 48°/s and (c) 72°/s.
indicates that coke collapses less at higher rotating speed. Figure 7 presents the collapse starting and ending positions, and collapse region span and Fig. 8 shows the SI for different size cokes in collapse region at different rotating speeds. It can be seen from Fig. 7 that the collapse starting and ending positions increase with the rotating speed increasing, and the starting position increases more than the ending position. The reason is that the burden stream width increases with the rotating speed increasing, which results in sinter spreading up on the coke layer surface. This is also the cause of collapse region span. It should be noticed that the coke collapse amount is small even though the collapse region is not narrow. It can be seen from Fig. 8 that cokes segregate much along radius at 24°/s rotating speed while they segregate much close to collapse ending position at 48°/s and 72°/s rotating speed. The absolute values of different size cokes’ SI are smallest for 72°/s rotating speed. This indicates that cokes segregate lightest among all different rotating speeds. Therefore, higher rotating speed is recommended for practical operation.

3.4. Sinter Amount

The chute rotates for 1 ring, 3 rings and 5 rings at fixed 30° chute angle. The coke collapse amounts are 300.2 kg, 940.0 kg and 1479.2 kg for 1 ring, 3 rings and 5 rings, respectively. The coke collapse amount increases significantly with the increase of sinter amount. This indicates that the more sinter amount is, the more severe coke collapse is. Figure 9 shows the collapse starting and ending positions, and collapse region span and Fig. 10 illustrates the SI for different size cokes in collapse region at different sinter amounts. It can be seen that the collapse starting position increases with the sinter amount increasing while the ending position decreases. And the collapse region span also increases with the increase of sinter amount. This can be interpreted as that the coke collapse “spreads up” with the increase of sinter amount, and the coke rolls more towards center than those towards wall. The reason is that the slope of coke funnel helps cokes to roll more easily towards center. It can be seen from Fig. 10 that values of different size cokes’ SI almost decrease along radial direction. The values increase with the increase of sinter amount and they increase more close to collapse ending position while less close to collapse starting position. This indicates that size segregation of coke collapse becomes severe when the sinter amount increases and the segregation is heavier close to collapse ending position. $SI_L$ and $SI_M$ are almost negative while $SI_S$ is almost positive at different sinter amounts. This implies that large and medium size cokes roll more than small size cokes. The reason is that larger size particle has better rollability than smaller size particle and small size particle can easily penetrate to the void between particles. Therefore, the sinter amount affects more not only the coke collapse amount but also the collapse segregation degree.
The sinter amount should be small enough with permission of practical operation.

4. Conclusion

Coke collapse is investigated in the upper part of blast furnace based on a three dimensional model using DEM in the present work. The effects of chute angle, rotating speed and sinter amount on the coke collapse amount, collapse region span and radial segregation index are also studied. The conclusions can be summarized as follow.

1. Coke profile changes much after its collapse and the collapse region accounts for 41.3% of furnace radius in the base model, which affects the radial burden distribution a lot and further the practical operation.

2. If the sinter amount for a fixed chute angle is small, the chute angle should be larger than the critical value due to small coke collapse amount, light coke size segregation along radial direction. If it is large, the chute angle should be smaller than the critical value due to small coke collapse amount, narrow collapse region and light coke size segregation close to collapse starting position.

3. The coke collapse starting position, ending position and region span increase a little with the increase of rotating speed. However, the coke collapse amount is small and the coke size segregation is light along radius at higher rotating speed. Therefore, the chute rotating speed should be higher with the permission of operation condition.

4. The coke collapse starting position, ending position, region span and segregation index change significantly with the increase of charged sinter amount. Therefore, the sinter amount for a fixed chute angle should be small in order to obtain small collapse amount and light coke size segregation.

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