Causes of Particle Trajectory Fluctuation on the Rotating Chute in Circumferential Direction at Bell-less Top with Parallel Type Hoppers

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Uneven burden distribution at bell-less top has a negative influence on the smooth operation of blast furnace with parallel type hoppers. Although previous works agreed that the initially oval-shaped particle trajectory on the chute causes the above-mentioned segregation, the subsequent particle trajectory fluctuation against the circumferential direction was still not fully understood. As a result, this work employs both the discrete element method (DEM) simulation and the theoretical model calculation, to quantitatively elucidate the causes of particle fluctuating behaviors on the rotating chute. The consistent results show that, on the one hand, a sine-like particle velocity distribution causes the Coriolis force to have a maximum magnitude around 120 deg while a minimum around 300 deg in the circumferential direction. On the other hand, the alternately sparse and intensive granular flow on the chute causes the particle mass flow rate to present a sine-like result with a maximum rate around 220 deg while a minimum around 60 deg. The superposition of two results contributes to the particle trajectory fluctuation on the rotating chute in the circumferential direction at bell-less top with parallel type hoppers.

KEY WORDS: particle trajectory fluctuation; coriolis force; mass flow rate; circumferential segregation; parallel type hopper.

1. Introduction

Burden distribution at the bell-less top blast furnace with parallel type hopper has a great influence on gas flow distribution and heat transfer, thus directly determining the smooth operation and energy efficiency in practical production. When discharged from one of the parallel type hoppers, the particles do not flow along the throat center, but flow close to the wall at the opposite of the working hopper. Thereafter, the particles collide and form an oval-shaped trajectory on the chute.1-3) Lab-scale experiments,4,5) theoretical model based on force analysis, and discrete element method (DEM) simulations,6-8) were all employed to investigate the imbalance behavior at bell-less top with parallel type hopper. Xu,6) Ho,9) Zhao et al.10) all agreed that the uneven burden distribution was mainly caused by the variation of colliding point on the chute. However, the subsequent particle trajectory fluctuation on the rotating chute was still not fully understood. For instance, Kajiwara11) and Shirsath et al.12) found that the Coriolis force causes the granular flow to deflect in the cross-section of the chute, but such a trajectory fluctuation against the circumferential direction is not clearly demonstrated. On the contrary, Narita et al.13) attributed the change in the particle trajectory to the interaction between the centrifugal force and the named curvature force. Therefore, it is essential to elucidate the reasons for the particle trajectory fluctuation in the circumferential direction at the bell-less top with parallel type hoppers.

In this study, both DEM and theoretical models are first established and validated. The acting forces on the particles and the mass flow rate are quantitatively analyzed in the circumferential direction, in order to elucidate causes of particle trajectory fluctuation on the rotating chute. The results show that, as the chute rotates, the initial oval-shaped collision leads to the periodic variation of particle velocity and alternately sparse and intensive granular flow on the chute. As a result, not only the Coriolis force, but also the mass flow rate presents a sine-like relationship in the circumferential direction. Therefore, both factors simultaneously affect particle trajectory fluctuation in the circumferential direction at bell-less top with parallel type hoppers.
2. Models Description

2.1. DEM Model

DEM, proposed by Cundall and Strack,\textsuperscript{14)} provides a deep understanding on particulate behaviors in the different fields. Its principle can be found anywhere, as well as in the authors’ previous work.\textsuperscript{3,15,16)} Moving particles undergo translational and rotational motions in a granular system, and the involved forces are determined by the Newton’s second law of motion. In the DEM, the particle contact model, as illustrated in the Fig. 1, is represented by a spring and a dashpot, which correspond to the elastic and plastic nature of particles in the normal direction, respectively. In the tangential direction, the model consists of a slider, a spring and a dashpot. The governing equations for the interactions between particles \(i\) and \(j\) can be expressed as:

\[
\frac{m_i}{\text{d}t} = \sum_k (F_{\text{cn},ij} + F_{\text{ct},ij} + F_{\text{dn},ij} + F_{\text{dt},ij}) + m_i g \quad \ldots \ldots \ldots (1)
\]

\[
I, \frac{d\omega_i}{\text{d}t} = \sum_k T_{ij} \quad \ldots \ldots \ldots (2)
\]

where \(m_i\), \(I_i\), \(u_i\), and \(\omega_i\) represents the mass, moments of inertial, translational velocity, and angular velocity of particle \(i\), respectively. The forces are the gravitational force \(m_i g\) and the inter-particle forces, which include the normal and tangential contact forces, \(F_{\text{cn},ij}\) and \(F_{\text{ct},ij}\), and damping forces, \(F_{\text{dn},ij}\) and \(F_{\text{dt},ij}\). The parameters and particle properties used for DEM simulation are collected in the Table 1, and the geometric dimensions and corresponding bird’s-eye view of bell-less top is shown in the Fig. 2.

\[\text{Parameters} \quad \text{Values}\]
\| Diameter of particles [mm] & 35 \\
\| Particle density [kg/m}^3 & 3 300 \\
\| Poisson’s ratio [-] & 0.25 \\
\| Young’s modulus [G Pa] & 3.50 \\
\| Friction coefficient [-] & 0.43 \\
\| Time step [s] & \(1 \times 10^{-3}\) \\
\| Rotation speed of chute \(\omega\) [rad/s] & \(4 \pi/15\) \\

2.2. Theoretical Model

The particles, discharged from bell-less top with the parallel hoppers, are easy to decenter when passing through the vertical chute. Hence, the colliding points on the chute form an oval-shaped trajectory as the chute rotates.\textsuperscript{6,17)} Thereafter, the applied forces on the particle flowing along the chute are schematically show in the Fig. 3, and the corresponding

![Fig. 1. Schematic diagram of the interaction forces between two adjacent particle \(i\) and \(j\) in the DEM simulation. (Online version in color.)](image1)

![Fig. 2. The geometric dimensions and the bird’s-eye view of bell-less top with parallel type hoppers.](image2)
force balanced equations are Eqs. (3) and (4). Besides, the parameters used for theoretical model calculation are summarized in the Table 2.

When the particle strikes the chute, its further motions can be clarified into two directions, namely the climbing motion in the cross-section direction and the sliding motion along the axial direction. Although a particle is subjected to the individual forces, such as the gravitational force \( \mathbf{G} = m g \), the reaction force \( \mathbf{F}_R \), the friction force \( \mathbf{F}_f \), the centrifugal force \( \mathbf{F}_c = -m \omega \times (\omega \times \mathbf{r}) \) and the coriolis force \( \mathbf{F}_r = 2m(\mathbf{v} \times \omega) \), the involved forces in the cross-section direction (denoted by subscript ‘cs’) apparently affect the particle climbing motion in the cross-section of the chute, and subsequently contributes to the difference in the discharge position.

\[
\begin{align*}
\frac{d \mathbf{R}}{dt} &= -g \cdot \sin \alpha \cdot \mathbf{v} \cdot \cos \theta + \mathbf{R} \cdot \sin \theta \cdot \cos \theta \cdot \mathbf{v}^2 + 2\omega \cdot \\
2\omega \cdot \left( y \cdot \sin \alpha \right) - \mathbf{R} \cdot \cos \theta \cdot \cos \alpha \cdot \mathbf{v}^2
\end{align*}
\]

\[\omega^2 \cdot \cos \alpha \cdot \sin \theta - \mu \cdot \mathbf{F}_N \cdot \frac{d \mathbf{R}}{dt} \quad \text{subjected to} \quad R \left( \frac{d \mathbf{R}}{dt} \right)^2 + \left( \frac{d \mathbf{R}}{dt} \right)^2 \quad \text{Eq. (3)}\]

Table 2. The parameters for theoretical model calculation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chute length [m]</td>
<td>4.4</td>
</tr>
<tr>
<td>Chute tilting distance [m]</td>
<td>0.4</td>
</tr>
<tr>
<td>Chute radius [m]</td>
<td>0.4</td>
</tr>
<tr>
<td>Chute tilting angle [deg]</td>
<td>30.0</td>
</tr>
<tr>
<td>Ore diameter [mm]</td>
<td>35.0</td>
</tr>
<tr>
<td>Ore density [kg/m³]</td>
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</tr>
<tr>
<td>Stock line [m]</td>
<td>1.5</td>
</tr>
<tr>
<td>Ore batch weight [t]</td>
<td>75.0</td>
</tr>
</tbody>
</table>

Fig. 4. Definitions of three rotating angles in the circumferential direction. (Online version in color.)

3. Results and Discussion

3.1. Models Validation

The DEM and theoretical models are firstly validated against the results from the reference. Three chute rotating angles are defined in the Fig. 4 to distinguish the quantitative results. The chute starts to rotate clockwise from 270 deg in the bird’s-eye view. When the particle strikes the chute, reaches the chute end, and falls into the sampling boxes below, its rotating angles are marked as \( \beta_{c} \), \( \beta_{e} \), and \( \beta_{s} \), respectively.

The chute inclination angle \( \alpha \) is 30 deg. When the ore particles discharged from the left hopper, their circumferentially flow positions are determined by the DEM simulation and theoretical model calculation respectively. As is illustrated in the Fig. 5(a), the average distance between the particle furthest falling point and the center in the DEM simulation is measured as the flow position, whereas the theoretical model can directly predict the flow position based on single-particle force balance. Both results are compared against the measurement from the literature in the Fig. 5(b). All the results predict the consistent flow position segregation in the 202.5 deg circumferential direction, and the furthest distances from the center are measured as 2940 mm (by DEM simulation), 2600 mm (by theoretical model calculation), and 2950 mm (from reference) respectively. The slight difference between the DEM simulation and literature attributes to particle size distribution. The previous work has used a size range of 20–37.5 mm,
while this study prefers an average particle size of 35 mm. Besides, the theoretical model predicted distance is shorter than the counterparts in the DEM simulation by about 11.6%. Because the theoretical model is built on the forces balance of a single particle, and the interaction among the particles is ignored.

Besides, the particle mass distributions are also considered for the model validation. As is schematically shown in the Fig. 6(a), there are 30 identical sampling boxes (100 mm × 400 mm) placed in each radial direction (0 deg, 90 deg, 180 deg and 270 deg). The mass of particles in each box is measured, and the corresponding mass ratio is determined by dividing the total mass of the particles in all 30 boxes. The particle mass ratio distributions in the above-mentioned four radial directions are demonstrated in the Fig. 6(b). The particles accumulate and form a peak between 0.4 and 0.6 normalized radial distance. Besides, the mass ratio in the 270 deg circumferential direction is smaller than that in the other directions by 14% at most. Such a particle mass segregation behavior in the circumferential direction agrees with the result reported in the reference 13).

Fig. 5. (a) Schematic diagram of particle flow position measurement in the DEM simulation, (b) comparison of particle flow positions by the DEM simulation, the theoretical model calculation, and the reference 13) in the circumferential direction. (Online version in color.)

Fig. 6. (a) Schematic diagram of the sampling method in the DEM simulation, (b) the particle mass ratio distributions in the four radial directions. (Online version in color.)

Overall, the particle segregation behaviors in terms of the flow position and the mass ratio distribution from this work are quite consistent with the results from the reference, which proves that the established DEM and theoretical models are reliable for the following analysis.

3.2. Analysis of the Acting Forces on the Particles in the Cross-section of the Rotating Chute

In the cross-section of the rotating chute, the acting forces on the particles are illuminated in the Fig. 7. The gravitational force, denoted by \(G_{CS}\), is along the vertical downward direction, and the corresponding reaction force, denoted by \(F_{N-CS}\), is pointing to the center of the cross-section. The centrifugal force and the Coriolis force, denoted by \(F_{C-CS}\) and \(F_{c-CS}\) respectively, are along the tangential upward direction, while the friction force, denoted by \(F_{f-CS}\), is in the opposite direction. Therefore, both the centrifugal force and Coriolis force drive the granular flow to deflect in the cross-section of the chute, while the gravitational force and friction force would like to pull it back. In the DEM simulation, the steady deflection angles of the granular flow centroid at the end of the chute are measured as 18.2, 23.1, 21.9 and 17.2 deg when the chute rotates to 0, 90, 180 and 270 deg respec-
tively. Given that the force directions are not change much in the circumferential direction, 20 particles in each direction are randomly selected from the DEM simulation to further calculate the average magnitudes of the individual forces, and the results are compared in the Fig. 8(a). First of all, the magnitude of the Coriolis force is found to be at least fifteen times greater than the centrifugal force, so the Coriolis force plays a key role of deflecting the granular flow in the

![Fig. 7](image-url)  
Fig. 7. The acting forces induced deflection of the granular flow in the cross-section of rotating chute demonstrated by the DEM simulation. (Online version in color.)

![Fig. 8](image-url)  
Fig. 8. (a) Comparison on the magnitudes of acting forces on the particles in the cross-section of chute, (b) the particle velocity distribution at the end of chute in the circumferential direction. (Online version in color.)
cross-section of the chute. Second, it is quite interesting to figure out that the magnitude of the Coriolis force demonstrates a sine-like curve with a maximum magnitude around 120 deg while a minimum around 300 deg, which make a direct influence on the deflection angle of the granular flow. For instance, the magnitude of the Coriolis force is 0.49 N in the 180 deg circumferential direction, while 0.46 N in the 270 deg direction. Therefore, the deflection angle in the cross-section decreases from 21.9 deg to 17.2 deg.

However, why the magnitude distribution of the Coriolis force presents a sine-like behavior? 20 particles are randomly selected, and their velocities at the end of the chute are depicted with respect to the circumferential direction in the Fig. 8(b). The similar sine-like distribution of the particle velocity, which arises from the initial oval-shape collision trajectory on the chute, helps understand the above-mentioned Coriolis force distribution behavior.

3.3. Analysis of the Particle Mass Flow Rate on the Rotating Chute in the Circumferential Direction

The particle mass flow rate at the end of the rotating chute is also analyzed by both the DEM simulation and theoretical model calculation. Since the particle mass flow rate in the tapered throat (MF_t) is a constant, the continuum flow is discretizing into the individual ones with certain mass (MF_t/Δt) in the theoretical model, where Δt is the time step for the calculation iteration. If the total moving time of an individual flow on the chute is t_1, and that of the subsequent individual flow is t_2. The mass flow rate (MF) at the end of the chute can be estimated by Eq. (5). All results are compared in the Fig. 9.

\[ MF = \frac{MF_t \cdot \Delta t}{t_2 - t_1 + \Delta t} \] ............................(5)

First of all, either the DEM simulation or the theoretical model calculation predicts a sine-like distribution of the particle mass flow rate in the circumferential direction. The greatest mass flow rate is 2 743 kg/s (by theoretical model calculation) or 2 789 kg/s (by DEM simulation) when the chute rotates to around 220 deg. The smallest one is 2 293 kg/s (by theoretical model calculation) or 2 381 kg/s (by DEM simulation) around 60 deg. Secondly, the mass flow rate in the circumferential 180 deg is greater than that in the 0 deg by approximately 190 mm. Thirdly, when the peak and trough results in the 225 deg and 65 deg directions are further compared by the DEM simulation, the distinguished difference in the discharge height can reach as great as 430 mm. Therefore, the sine-like behavior of the particle mass flow rate in the circumferential direction definitely causes the particle discharge positions to fluctuate periodically at the end of the rotating chute.

In order to further explain the above-mentioned behavior of the particle mass flow rate, a schematic diagram is shown in the Fig. 10. When the particles are discharged from the chute...
left hopper (refer to the Fig. 4), the mass flow rate in the throat is a constant. Subsequently, when the chute rotates from 270 deg to 0 deg, then to 90 deg in the Fig. 10(a), the initial striking point of the decenter granular flow moves upward along the axial direction of the chute. Therefore, the continuously falling particles on the chute become sparse to some degree. On the contrary, when the chute rotates from 90 deg to 180 deg, then to 270 deg in the Fig. 10(b), the corresponding striking point move downward, so the falling particles partially overlap the ones already flowing on the chute, which makes the granular flow crowded or intensive. Therefore, as the chute rotates, the alternately sparse and intensive granular flow causes the sine-like distribution of the particle mass flow rate in the circumferential direction.

4. Conclusions

Aiming to elucidate the particle trajectory fluctuation on the rotating chute at bell-less top with the parallel hoppers, the DEM and theoretical models, after validated against the literature’s results, are employed for this work. The acting forces on the flowing particles and the particle mass flow rate are quantitatively analyzed, to highlight the causes of particle trajectory fluctuation on the rotating chute in the circumferential direction.

The results show that due to the initial striking oval-shape trajectory on the chute, the particle velocity distribution in the circumferential direction causes the Coriolis force to have a maximum magnitude around 120 deg while a minimum around 300 deg, while the alternately sparse and intensive granular flow on the chute causes the particle mass flow rate to present a sine-like result with a maximum rate around 220 deg while a minimum around 60 deg. Both the sine-like distribution behaviors co-explain the circumferential fluctuation of the discharge position height on the rotating chute at bell-less top blast furnace with parallel type hoppers.

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REFERENCES