Modeling the Gas-solid Flow in the Reduction Shaft of COREX

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COREX is a promising alternative to blast furnace ironmaking. It includes two main reactors: a reduction shaft (RS) for the direct reduction of iron ore and a melter gasifier for the melting reduction of directly reduced iron. This work uses a two-dimensional slot model to investigate the gas-solid flow in the RS by a combined computational fluid dynamics and discrete element method approach. The three-dimensional flow of cohesive solids is then examined for three RS designs by the discrete element method. The effects of gas flow, the stickiness between particles, the rotational speed of screws, and different designs are depicted in terms of gas-solid flow pattern, overall bed pressure drop and solid flowrate. The results show that the effect of gas flow is insignificant on gas-solid flow pattern due to the small gas-solid interaction forces under the considered conditions. Solid flow varies in a complex manner with the rotational speed of screws and the sticking force, and a correlation is formulated for predicting the solid flowrate based on the simulated results. It is also shown that the effect of geometrical design on solid flow is complicated and significant. Caution should be taken for any changes in the design. The findings should be useful for the design, control and optimization of the RS operation.

KEY WORDS: COREX; discrete element method; reduction shaft; screw feeder; sticking force.

1. Introduction

Blast furnace is the major workhorse to produce liquid iron for steelmaking with the current development of technology. It has a long history, and has evolved into a reactor with high energy efficiency. However, it needs coke as a major fuel to reduce iron ore although different technologies such as pulverized coal injection have been developed to reduce the consumption of coke. With the increasing demand for environment protection and the diminishing high quality coking-coal resources, the cost to produce liquid iron with blast furnace becomes a significant issue.

To eliminate the use of coke, different processes such as FINEX, Hismelt and COREX have been developed in recent decades.1) Of these, COREX is the first commercialized process, and there are several plants in operation with different capacities. It is a two-stage process using a reduction shaft (RS) and a melter gasifier (MG). In this process, iron ore, together with other raw materials, is first fed into RS where it is reduced to produce directly reduced iron (DRI) with a metallization rate around 80%. DRI and coal are then fed into MG by screw feeders for the melting reduction. Being a relatively new process, COREX is not well understood, and fundamental research is needed in order to overcome various problems such as high fuel consumption and short campaign life.2)

In the past, physical and mathematical models of various types have been applied to understanding the coupled gas-solid flow and thermo-chemical behaviors in COREX. While it is not easy to conduct physical experiments even at a lab scale, mathematical models can provide some useful information. In particular, steady state models with some assumptions have been proposed to understand the heat and mass balance.3–7) These models are useful for an overall understanding of the process. Nevertheless, the transient features are often missing in these models, which can play a significant role in the operation of the process. To overcome this problem, the discrete element method (DEM)8) has recently been used to study some process phenomena such as dynamic burden distribution9,10) and particle descending velocity in the bottom part of a reduction shaft.11) In these studies, the effects of some parameters such as distributor angle and rotating speed on burden profile and coke size segregation were investigated. While these studies provide useful information, some important phenomena have not been addressed. For example, the stickiness between particles, induced by reduced elastic modulus of relevant materials and in particular, liquid bridge as a result of high temperature operation and reduction reaction of iron ore, may create a problem, e.g. the formation of scaffold, in the discharging of solids. In fact, significant stickiness between iron ore particles is observed in a direct reduction process within the temperature range of 600 to 675°C.12) It is important to understand and hence control this effect.

In this work, the effect of gas flow on gas-solid characteristics is first examined at different inlet gas velocities in a two-dimensional (2D) slot model of RS by a combined

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computational fluid dynamic (CFD) and DEM approach. Then, the flow of sticking solids is investigated in a three-dimensional (3D) RS by DEM. The effects of some parameters such as the stickiness between particles, the rotational speed of the discharging screws and different designs of RS on solid flow are illustrated. The findings of this work should be useful for the design, control and optimization of the RS operation.

2. Model Description

In this study, the gas-solid flow in a RS is considered to be composed of a discrete solid phase and a continuum gas phase (air to be specific). The solid phase is described by the DEM. Thus a particle has two types of motion: translational and rotational. While moving, the particle may interact with its neighboring particles and/or walls, through which the momentum and energy exchange takes place. At any given time \( t \), the equations governing the motions of particle \( i \) of mass \( m_i \) and radius \( R_i \) can be written as:

\[
m_i \frac{dv_i}{dt} = \sum_j (f_{\text{ij},d} + f_{\text{ij},v}) + f_{\text{pf},i} + m_i g, \quad \text{(1)}
\]

and

\[
l_i \frac{d\omega_i}{dt} = \sum_j (T_{\text{ij},d} + T_{\text{ij},v}), \quad \text{(2)}
\]

where \( v_i \) and \( \omega_i \) are the translational and rotational velocities, and \( l_i = 2/5m_iR_i^2 \) is the moment of inertia of the particle. The forces involved are: particle-fluid interaction force \( f_{\text{pf},i} \), the gravitational force \( mg \) and the forces between particles (and between particles and walls) which include the elastic force \( f_{\text{ij},e} \), viscous damping force \( f_{\text{ij},d} \) and the sticking force \( f_{\text{ij},v} \). The torque acting on particle \( i \) due to particle \( j \) includes two components: \( T_{\text{ij},d} \) which is generated by the tangential force and causes particle \( i \) to rotate; and \( T_{\text{ij},v} \) which, commonly known as the rolling friction torque, is generated by the asymmetric normal contact forces and slows down the relative rotation between contacting particles.\(^{13}\) If particle \( i \) undergoes multiple interactions, the individual interaction forces and torques are summed up for all particles interacting with particle \( i \). Most of the equations for determining the flows and torques have been well established,\(^{16,21,22}\) as given in Table 1.

<table>
<thead>
<tr>
<th>Force or torque</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal elastic force, ( f_{\text{et},i} )</td>
<td>(-\frac{4}{9}E \sqrt{\frac{\pi}{3}} \rho \delta_{\text{ij}}^2 n )</td>
</tr>
<tr>
<td>Normal damping force, ( f_{\text{dn},i} )</td>
<td>(-c_1 (6m_i \rho \sqrt{\pi} \delta_{\text{ij}}^2) v_{\text{ij}} )</td>
</tr>
<tr>
<td>Tangential elastic force, ( f_{\text{et},i} )</td>
<td>(-\mu_i k_{\text{ij}} (1 - (1 - \delta_{\text{ij}}) / \delta_{\text{max}})^2 \delta_{\text{ij}} )</td>
</tr>
<tr>
<td>Tangential damping force, ( f_{\text{dn},i} )</td>
<td>(-\varepsilon (6m_i \rho \sqrt{\pi} \delta_{\text{max}}^2) v_{\text{ij}} )</td>
</tr>
<tr>
<td>Coulomb friction force, ( f_{\text{cf},ij} )</td>
<td>(-\mu_i k_{\text{ij}} \delta_{\text{ij}} \delta_{\text{ij}} )</td>
</tr>
<tr>
<td>Torque by tangential forces, ( T_{\text{et},ij} )</td>
<td>(R_i \times (f_{\text{et},ij} + f_{\text{et},ij}))</td>
</tr>
<tr>
<td>Rolling friction torque, ( T_{\text{rf},ij} )</td>
<td>(\mu_i k_{\text{ij}} \delta_{\text{ij}} \delta_{\text{ij}} )</td>
</tr>
<tr>
<td>Particle-fluid drag force, ( f_{\text{pf},i} )</td>
<td>(0.125C_{\text{df}} \rho_d \pi d_i^2 \varepsilon_i</td>
</tr>
<tr>
<td>Pressure gradient force, ( f_{\text{pg},j} )</td>
<td>(-\nabla \rho_j )</td>
</tr>
</tbody>
</table>

where \( 1/m_{\text{df}} = 1/m_1 + 1/m_2 + 1/R_1 + 1/R_2 \), \( E = \frac{2(1 - \nu)}{\mu} \), \( \mu = \frac{\mu_i}{\mu_i + \mu_d} \), \( \delta_{\text{ij}} = \frac{|\delta_{\text{ij}}|}{|\delta_{\text{ij}}|} \), \( \delta_{\text{ij}} = \frac{\delta_{\text{ij}}}{|\delta_{\text{ij}}|} \), \( R_i = R (1 - \nu)/(R_1 + R_2) \), \( \delta_{\text{max}} = \delta_{\text{ij}} \), \( v_{\text{ij}} = v_i - v_j + \alpha_i \times \mathbf{R}_i - \alpha_j \times \mathbf{R}_j \), \( \varepsilon_i = (v_i \times n) \cdot n \), \( \varepsilon_{\text{ij}} = (v_{\text{ij}} \times n) \times n \), \( e_i = 1 - \sum_j V_j / (2 \delta_{\text{ij}}^2) \), \( \delta_{\text{ij}} = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \), \( \delta_{\text{ij}} = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \), \( \delta_{\text{ij}} = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \), \( \delta_{\text{ij}} = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \), \( \delta_{\text{ij}} = 1.05 \), \( |\delta_{\text{ij}}| = 1.05 \). Note that tangential forces \( f_{\text{et},ij} + f_{\text{et},ij} \) should be replaced by \( f_{\text{et},ij} \) when \( \delta_{\text{ij}} \geq \delta_{\text{max}} \) has been used conditionally. In this work, Set I is used. Thus, the conservation of mass and momentum in terms of the local averaged variables over a computational cell are given by:

\[
\partial_t (\rho_j \varepsilon_j) / \partial t + \nabla \cdot (\rho_j \varepsilon_j \mathbf{u}_j) = 0, \quad \text{(3)}
\]

and

\[
\partial_t (\rho_j \varepsilon_j \mathbf{u}_j) / \partial t + \nabla \cdot (\rho_j \varepsilon_j \mathbf{u}_j \mathbf{u}_j) = -\nabla \rho_j - \nabla \cdot (\rho_j \varepsilon_j \mathbf{g}), \quad \text{(4)}
\]

The numerical method for CFD-DEM simulations has been well established.\(^{16,21,22}\) The coupling scheme used here is the same as before, not described here for brevity.

An in-house CFD code is used, which can accommodate the complicated geometries and the rotational motion of the screws. The boundary walls and the screws are represented by small triangular meshes, and the contacts between a wall and particles can be detected and treated similarly to particle-particle contacts. The geometries based on the generated meshes are smooth as shown in Fig. 1(b). Further decrease in mesh size does not produce any observable differences of results. In fact, the in-house DEM code has been applied to different granular systems successfully.\(^{23-25}\)

There are different models for the sticking force with different realization complexities, e.g., the van der Waals force associated with fine particles\(^{26,27}\) and the capillary force with wet particles.\(^{28,29}\) In the COREX process, stickiness between particles is complicated, depending on material properties such as particle sizes and shapes and on the possible change of a given system due to heat transfer and chemical reactions. The sticking force is here assumed in the range of 0–25 mg. This is based on the previous finding that agglomeration becomes significant when the sticking force between particles is over 15 mg in fluidized beds\(^{30}\) and the knowledge that the sticking forces for the transitions between different flow regimes vary with flow conditions.
and particle properties. Since our aim here is to establish a general understanding of the sticking force between particles on solid flow, a simplified sticking force model is used to reduce the computational requirement while reasonable and general results can be obtained. That is, a sticking force force, whose magnitude is set to be proportional to the gravity force of a particle (mg, given by $\rho g d^3/6$), is assumed when the gap between two particles or between a particle and a wall is less than a certain value. A similar approach has been used in the study of the effect of cohesive force on fluidization\(^{30}\) and on solid flow in screw feeders.\(^{31}\) Note that the test results show that there is no significant effect of the gap limit when it is less than 1% particle diameter. The particle-wall interaction is treated similarly and a rotating wall boundary is implemented for the screws.

3. Simulation Conditions

Two systems are used as shown in Fig. 1. One is a 2D slot model for the examination of the effect of gas flow. The other is a 3D RS model with a preset stagnant zone for the study of the effects of the sticking force, rotational speed of the screws and different RS designs. Using a large particle size and a scaled down model is a common practice in process modeling by DEM or CFD-DEM approach.\(^{32}\) The main dimensional parameters for the RS model are given in Fig. 1(a), which is 1/4 of a practical RS. In the 2D simulations, the fluid and solid phases are calculated and coupled together by the CFD-DEM approach, which is computationally more demanding than the 3D DEM simulation. Hence, a large particle size (60 mm) is used in the CFD-DEM simulations. The properties of particles used in the 3D DEM study are given in Table 2, which are close to those of iron ore pellets except for the particle size. Note that the effect of particle properties such as density and diameter on the phenomena discussed in the present study is actually minor. The parameters for the 2D slot model are similar except that particle diameter $d_p$ is 60 mm and the bed thickness is eight particle diameter ($8d_p$). Totally, 25 000 particles are used in the 2D slot model. Two gas inlets and two discharging zones are schematically shown in Fig. 1(a). Gas is introduced at the inlets and particles are removed from the discharging zones and recycled to the top. The standard gas velocity 4 m/s for the 2D model is obtained according to the real gas flowrate in plant operation and the volume ratio between the real system and the scaled down model. Periodic boundary conditions are applied to solid phase along the front and rear direction to eliminate the effect of walls. For the above geometry, 2D CFD and 3D DEM are used as done by Feng et al.\(^{22}\)

In the 3D RS model, particles are initially generated randomly and allowed to settle under the gravity to reach a macroscopically static state in the system. Then, the rotational motion of the screws is introduced at a given time for the 3D model. The rate of continuous charging is set according to the predicted flowrate under various conditions to maintain a stable fill level of particles in the RS. While the burden distribution plays an important role in the control of gas flow and hence chemical reactions in the RS, this study focuses on the solid flow associated with a simplified burden charging.

In the RS, gas-solid flow experiences a complicated thermo-chemical behavior. However, as a first step to develop a comprehensive CFD-DEM RS model, this study only examines the flow behavior, and the thermo-chemical behavior will be studied in the future. Hence, the stickiness between particles is assumed to be uniform in the present RS model.

4. Results and Discussion

Coupled gas-solid flow in the 2D slot model and sticking solid flow in the 3D model are investigated in this study. The combined CFD-DEM approach as well as the DEM method has been extensively tested in various systems.\(^{23–25,31–33}\) Their application here should at least provide some qualitative, if not quantitative, results useful to understand the RS process.

### Table 2. Particle properties in the simulation.

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle diameter $d_p$, mm</td>
<td>50</td>
</tr>
<tr>
<td>Density $\rho_p$, kg/m³</td>
<td>2.500</td>
</tr>
<tr>
<td>Young’s modulus, Pa</td>
<td>$1 \times 10^7$</td>
</tr>
<tr>
<td>Poisson’s ratio, –</td>
<td>0.3</td>
</tr>
<tr>
<td>Friction coefficient, –</td>
<td>0.3</td>
</tr>
<tr>
<td>Restitution coefficient, –</td>
<td>0.8</td>
</tr>
<tr>
<td>Time step, s</td>
<td>$7.60 \times 10^{-5}$</td>
</tr>
<tr>
<td>Total number, –</td>
<td>~160 000</td>
</tr>
</tbody>
</table>
4.1. Effect of Gas Flow

Here, the effect of gas flow is discussed at different inlet gas velocities with the particle discharge rate fixed at 289 kg/s for obtaining a macroscopically stable flow pattern in a short period.

The initial packed bed and snapshots of the flow patterns are shown in Fig. 2. A relatively uniform charge (or burden distribution) is adopted as its effect is not the focus of this study. Under the current simulation conditions, a relatively stable flow pattern is observed at 55 s, although some minor changes can be observed after this time. Due to the complicated geometry of the RS and the particle discharge, two main features are observed. The first is the slow motion of particles near walls. It is different to the no-slip boundary (namely, zero velocity at the wall) of a fluid. Granular flow normally has a slip at the boundary, although the motion is slow in the so-called shear zone mainly due to particle-wall friction. The other is the formation of different flow zones such as the plug flow zone at the top (I), the stagnant zone at the bottom (III), and the quasi-stagnant zone in-between (II), as schematically shown by dashed lines in the snapshot at 368 s. The motion of particles in the stagnant zone is slow. As seen from the snapshots at 55, 211 and 368 s, particles can exchange between the stagnant and quasi-stagnant zones due to the shear forces of the moving particles. These features reflect the complicated flow conditions in the RS.

Further analysis is carried out for gas flow and porosity distribution. The flow fields are similar at different inlet gas velocities (2–6 m/s) as shown in Fig. 3. The areas having small velocities generally correspond to the quasi-stagnant and stagnant zones of the solid flow. In the plug flow zone, the velocity is quite uniform, providing a good environment for iron ore reduction. No significant difference of porosity distribution is observed, indicating that gas flow has a minor effect on gas-solid flow pattern. This is expected because RS is normally operated as a moving bed. Here, the relative values of the bed pressure drop to the burden load (defined as the bed weight per cross-sectional area) are less than 2% (Fig. 4). Note that the cross-sectional area is obtained by multiplying the maximum width of the RS (2 150 mm as given in Fig. 1) and the bed thickness (8 particle diameters, 480 mm) and the bed weight is the weight of 25 000 particles with the density of 2 500 kg/m³ and the diameter of 60 mm. Although the particle size and the inlet gas velocity may affect the pressure drop overall or locally, this small
pressure drop reflects that gas-solid interaction forces are small and the gravitational force is dominant under the current conditions. It is different to the phenomena in blast furnace, where local fluidization of particles can be observed in the raceway region.\(^3\)\(^3\)\(^4\)\(^3\)

These results demonstrate that gas flow has a minor effect on the gas-solid flow pattern under the conditions considered. Hence, no gas flow is included in the following 3D model study, where the focus is solely on the solid flow. It should be noted that gas flow may play an important role if heat transfer and chemical reactions are considered, but this is beyond the scope of the present study.

### 4.2. Effects of the Sticking Force and the Rotational Speed of Screws

The sticking force between particles can cause problems such as scaffold formation and insufficient iron ore reduction. The factors affecting the sticking force include temperature, gas distributions and chemical compositions of the reducing gas and iron ore. All these factors are related to the gas-solid flow pattern. As the first step to establish a comprehensive understanding, this work focuses on the effects of sticking force and rotational speed of screws on the solid flow at ambient temperature.

With the increase of sticking force, as presented in the previous study of solid flow in a screw feeder,\(^3\)\(^1\) different flow regimes of solid flow can be observed. For negligible interparticle stickiness \((0–10 \text{ mg})\), the system is operated in a continuous flow regime, and particles can flow continuously into the screw casing, dragged by the screw and the gravity. For intermediate interparticle stickiness \((10–25 \text{ mg})\), the system is operated in an intermittent flow regime, and a strong force network may be formed, hindering particles from flowing into the voids generated by the screws. The flow is not smooth as a result of the combined effect of the formation of arches between particles and walls, and the perturbation of the rotating screw blades. When the stickiness is increased over a certain level \((> 25 \text{ mg})\), the system is in a stable arch flow regime. Solid flow is terminated completely because of the formed stable force network, which resists the perturbations of the screw blades. Note that the solid flowrate discussed are the time-averaged values of fluctuating flowrates over a period of macroscopically stable flow \((10 \text{ s})\). These observations of different flow regimes demonstrate that the solid flow of sticking particles in the RS is quite complicated. Hence, the optimization of the RS design and operation is a challenge.

Based on the present DEM simulations a correlation is formulated to quantify the effects of the sticking force and the rotational speed \((\omega)\), as given below:

\[
Q = A e^{f/8} + B 
\]

where \(Q\) is solid flowrate in terms of particle numbers; \(f\) is the magnitude of the sticking force; \(A = -(14.81 \omega + 0.49)\) and \(B = 258.11 \omega + 11.36\) are two coefficients related to the rotational speed of the screws. Note that the volumetric flowrate by particle number is adopted so that it can be converted to mass flowrate readily for different particle densities. Equation (5), established by curve-fitting, can describe the numerical predictions well as shown in Fig. 5. Hence, the proposed correlation could be used to estimate the solid flowrate as a function of the sticking force and rotational speed of the screws for the system considered. It should be noted that the values of the sticking force at which the solid flow transits from the continuous flow regime to the intermittent one, and then to the stable arch one are system-dependent. Further, coefficients \(A\) and \(B\) that are functions of the rotational speed should be adjusted for different applications. Moreover, it is likely that the effect of the sticking force in the 3D RS model with eight screws is slightly different from that in a screw feeder with one screw.\(^3\)\(^1\) However, both geometries retain the general form of Eq. (5) for the effect of the sticking force on the solid flowrate.

The mechanism behind the effect of the sticking force is similar to that identified in a screw feeder.\(^3\)\(^1\) With the increase of the sticking force, the force bridge formed between particles and the walls of the RS becomes stronger, which reduces the effect of gravitational force on the solid flow. Force arches, combined with the perturbations by the rotating screw blades, lead to the intermittent and stable arch flow regimes for highly sticking particles.

### 4.3. Effect of RS Design and Its Implications

The effect of three RS designs on the solid flow is examined in the present study. The first one tested is a simplified model without gas slots (Fig. 6(a)), the second one is a more realistic model with gas slots (Fig. 1(b)), and the third one is with gas slots and has two tubes installed for improving

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**Fig. 5.** Solid flowrate as a function of sticking force at different rotational speeds of screws. Symbols represent DEM predictions and lines are the fittings given by Eq. (5). (Online version in color.)

**Fig. 6.** Different RS designs: (a) simplified design; and (b) side and top views of the model with two tubes.
metallization of DRI (Fig. 6(b)).

The distribution of particle velocities varies initially and can reach a steady state within 10 s. Figure 7 shows typical snapshots of the steady flow in the simplified model, indicated by particle translational (|V|) and angular (|A V|) velocities. Note that the unit of translational velocity is \((d_p g)^{1/2}\), which can be converted to m/s by dividing 0.7 (i.e., \((d_p g)^{1/2}\)) under the current conditions. For example, reduced translational velocity 1.0 is equal to 1.43 m/s. The unit of angular velocity is \((g/d_p)^{1/2}\), which can be converted to rad/s by dividing 14.0 (i.e., \((g/d_p)^{1/2}\)). For example, reduced angular velocity 1.0 is equal to 0.07 rad/s. This treatment applies to other figures (Figs. 8–13) with reduced units in this work. These velocity distributions correspond to different flow zones. Hence, the following discussion is focused on one macroscopically stable instant.

In the simplified model, a man-made dead zone is set to avoid a slowly moving zone as used in plant operation. However, solid flow is still complicated as indicated by particle velocities in Fig. 8. For different rotational speeds of the screws, the distribution of particle velocities is similar. In the upper part of the RS it is generally a plug flow zone with small particle velocities, which largely corresponds to the shaft of a blast furnace. The most complicated flow zone

Fig. 7. Steady solid flow for the sticking force of 20 mg at a rotational speed of 240 rpm indicated by: (a) particle translational velocity (|V|) and (b) particle angular velocity (|A V|). The range of x coordinate for the sliced zone is \(-2 \sim 2d_p\). (Online version in color.)

Fig. 8. Particle velocity distribution at 10 s for different rotational speeds of screws (60 rpm: (a) and (b); 240 rpm: (c) and (d)) without the sticking force. The range of x coordinate for the sliced zone is \(-2 \sim 2d_p\). (Online version in color.)

Fig. 9. Particle velocity distribution at 10 s at a rotational speed of 240 rpm for different sticking forces: (a) and (b) 10 mg; and (c) and (d) 20 mg. The range of x coordinate for the sliced zone is \(-2 \sim 2d_p\). (Online version in color.)

Fig. 10. Particle velocity distribution at 10 s for a rotational speed of 600 rpm without sticking force: (a) angular velocity and (b) translational velocity. The range of x coordinate is \(-2 \sim 2d_p\). (Online version in color.)
is at the lower part where solid flow transits from a plug flow to quasi-stagnant (or funnel) one, driven by the rotating screws. A quasi-stagnant flow is observed near the preset man-made dead zone, mainly due to the wall boundary effect. The largest particle velocities are observed in screw casings where the interaction between particles and screw blades is strong. For different rotational speeds of the screws, the magnitude of particle velocities for 60 rpm rotational speed is smaller than that of 240 rpm, as expected. A large solid flowrate corresponds to a fast rotational speed of screws and hence large particle velocities. This implies that a large rotational speed of screws could enhance the rotational motion of particles and possibly reduce the period of static contacts between particles and the related sticking effect. But how the rotational speed will affect heat transfer and chemical reactions needs further investigation.

The sticking force affects solid flowrate of the system with screws, as shown in Fig. 5. Here the solid flow patterns corresponding to different sticking forces are further discussed. Figure 9 shows particle velocity distribution for different sticking forces in the simplified 3D model. With the increase of inter-particle stickiness, two main characteristics can be observed. The first one is that a large angle of repose for a strong sticking force is observed in the upper part as a result of the strong particle-particle interactions. The second is that large agglomerates are formed, as can be seen at the outlet. As a result, the solid flowrate is reduced, and an intermittent flow can be observed when the sticking force increases over a certain value.

With the introduction of gas slots, wall boundary becomes complicated. Note that the burden charge for the 3D models with gas slots is uniformly distributed in a circular region with an inner diameter of $4d_p$ and an outer diameter of $32d_p$. Both distributions of angular and translational velocities are shown in Fig. 10. The main difference compared to the simplified model is that the areas with large particle angular velocities are observed above and below the gas slots as shown in Fig. 10(a), due to the changes in the flow conditions or cross-sectional area of the RS. From the distribution of particle translational velocity in Fig. 10(b), the areas with small values are observed under gas slots, which is partly due to the increase of the cross-sectional area.

As with the simplified model, particle velocity distributions at different sticking forces are shown in Fig. 11 for the model with the gas slots. The two main characteristics discussed above can be observed clearly because of the different burden charge adopted. It can be seen that the sticking effect is enhanced by the complicated wall boundary. For the sticking force of approximately 25 mg, solid flow enters...
The effect of the sticking force in the model with two tubes is shown in Fig. 13. A large angle of repose is similarly observed for a strong sticking force in the upper part of the RS. A unique feature is that voids are observed downstream of the tubes and around the gas slots, which enlarge with the increase of the sticking force. Figure 13(c) shows that solid flow enters the stable arch flow regime for a sticking force of approximately 20 mg, which is smaller than 25 mg in the model without tubes shown in Fig. 5. The complicated structure of the RS enhances the effect of the sticking force on solid flow and changes the transitions between different flow regimes.

The tube design is a new feature of COREX C3000 in Baosteel, China. As observed in the actual plant operation, it indeed changes gas flow and improves reduction rate of iron ore. However, as discussed above, it affects the solid flow significantly. The new design should be improved to reduce its effect on the flow of sticking solids. It should be noted that the rotational speed of screws in plant operation is smaller than those used in this study. Nonetheless, similar phenomena are expected according to the results for different rotational speeds, as observed from Fig. 5.

5. Conclusions

In order to understand the gas-solid flow in the reduction shaft of COREX process, DEM and CFD-DEM techniques have been employed in the present study. In particular, CFD-DEM is used to investigate the effect of gas flow in a two-dimensional slot model, and a DEM model is used to investigate the three-dimensional flow of cohesive solids. The effects of gas flow, the sticking force, the rotational speed of the screws and three reduction shaft designs are discussed. The following conclusions can be drawn from the present study.

- Gas flow affects the solid flow pattern insignificantly under the considered conditions due to the small gas-solid interaction forces. This is reflected in the small overall bed pressure drop. Hence, the solid flow in the reduction shaft can be investigated by just considering the solid phase if the effects of other factors such as chemical reactions and heat and mass transfer are not necessarily considered.
- The sticking force between particles affects the solid flow characteristics significantly. When the stickiness is low, solids can be extracted continuously from the reduction shaft to the melter gasifier. If the stickiness is increased over a certain level (~10 mg under the conditions of this study), the solid flow becomes problematic and intermittent. When the stickiness is too large (>25 mg), solid flow could terminate completely. These are the collected outcomes of the formation of arches between particles and walls, and the perturbation introduced by rotating screws.
- The rotational speed of screws affects solid flow consistently within the range considered. A correlation can be formulated for predicting solid flowrate as a function of the sticking force between particles and the rotational speed of screws. The correlation is expected to be useful for plant operation with lower rotational speeds than those investigated.
- Reduction-shaft design affects the solid flow significantly. Particularly, the effect of particle stickiness can be
severe, affecting the reduction-shaft operation adversely depending on the chosen design. For example, the solid flow can stop at a lower stickiness (~20 mg) for the design with two tubes than that for the design without tubes (~25 mg). Thus, caution should be taken for any changes to the existing reduction-shaft design.

Based on the findings of this study on solid flow, more efforts should be made at least in two directions for the reduction shaft. The first lies in improving the screw discharging system to obtain smooth discharging flows. The other lies in optimizing reduction-shaft design to cope with as large stickiness as possible. These efforts may reduce the demand of raw materials. On the other hand, it should be noted that solid flow is just one of the important aspects of the performance. In order to attain a comprehensive understanding and to improve the energy efficiency of the whole reduction shaft process, heat and mass transfer, as well as chemical reactions, should be taken into account in the future studies.

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