DEM Study of Solid Flow in COREX Shaft Furnace with Areal Gas Distribution Beams

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In this work, a three-dimensional DEM-based model is used to investigate solid flow including burden descending behaviour and particle segregation in the shaft furnace of ironmaking COREX. The model was validated by the reasonable agreements between simulations and experiments. The results confirm that the Areal Gas Distribution (AGD) beams affect solid flow in the bustle zone significantly but slightly at the lower part of the furnace. A triangle-shaped free zone is observed below the AGD beams, which will be the main path for gas flow along the centre of shaft furnace. The AGD beams can lead to particle segregation in the shaft furnace. The coke and flux particles can roll easily from the centre to the zone below the AGD. As a result, the normalized mass fractions of coke and flux are larger than 1.0 near the screw outlet located below the AGD beams. In addition, three new designs of AGD beams are proposed in this work. The simulation results indicate that the design with three AGD beams is regarded as the optimal option due to uniform burden descent and convenient installation. The model provides a cost-effective tool to understand and optimize the solid flow in the shaft furnace of COREX.

KEY WORDS: DEM; COREX; ironmaking; solid flow.

1. Introduction

At present, more attention are attracted to global warming and CO₂ emission from coal-fired industries such as power plant and steel industry. In the latter, the cokemaking oven is a major CO₂ contributor. On the other hand, high quality coking-coal resources are draining and thus the coke is increasingly expensive. For these reasons, various alternative ironmaking technologies are developed in recent decades such as COREX, FINEX and HIsarna, which are designed to need less or even zero coke.^{1,2)} Among these technologies, COREX, a smelting reduction process, is regarded as a cost-efficient and environmental-friendly process, which produces hot metal from iron ore and coal.^{3–5)} Practically, it is a two-stage process that involves pre-reduction in a shaft furnace, followed by final reduction and separation in a melter gasifier (MG). In this process, lump ore, pellet, flux and in some cases a certain amount of coke are charged from the top of the shaft furnace. As the burden descends, lump ore and pellet are partially reduced to metallized iron (termed direct reduction iron, DRI) by reducing gas produced by the MG. Then the DRI and lump coal are fed into the MG by screw feeders. Physically, both shaft furnace and MG are typical counter-current reactors, in which reducing gases flow upward through the packed bed while the charged solid particles flow downward. In these flows, the motion of particles, as a densely packed bed, will

have a significant impact on the flow of other phases, and thus on operation efficiency of the entire production. That is, the transient features of solids are crucial in the COREX process.^{6–10)} Recently, a new technique, so-called Areal Gas Distribution (AGD), has been proposed and tested in the shaft furnace of COREX. In the tentative design, two AGD beams are installed. The AGD technology is proven effective in improving reduction rate in plant.^{11,12)} However, as a result of AGD installation, the in-furnace solid flow will be more complicated and thus may affect the burden descending velocity and possibly lead to particle segregation. Therefore, it is necessary to understand the effect of AGD on solid flow phenomena in the shaft furnace such as burden descending behaviour and particle segregation for optimal design and control of COREX.

In the past, many experimental studies have been carried out to understand burden descending behaviour in ironmaking blast furnace (BF).^{13–21)} Only a few experimental studies were conducted on solid flow in COREX shaft furnace.^{22–24)} For example, Lee investigated the solid flow profile and timeline of the packed bed in shaft furnace with and without a guiding cone.²²⁾ Zhou *et al.* studied the solid flow in COREX shaft furnace with AGD using a cold physical model,²³⁾ and investigated the influence of AGD on burden descending behaviour.²⁴⁾ These results are useful for understanding solid flow in shaft furnace. However, they can only provide understanding at macroscopic level.

To overcome this shortcoming, the so-called Discrete Element Method (DEM),²⁵⁾ which describes granular flow at an individual particle level, are widely used to study the

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fundamental behaviour of granular flow.^{26,27)} It has been used to study the solid flow in BF.^{28–31)} In recent years, some researchers have applied DEM to study the solid flow in COREX shaft furnace, such as dynamic burden distribution,^{9,32)} particle descending velocity at the bottom of shaft furnace,³³⁾ asymmetric solid flow,³⁴⁾ heat transfer in shaft furnace.³⁵⁾ These studies provide useful information on the solid flow in traditional shaft furnace. Furthermore, some studies are conducted about the effect of AGD on burden descending behaviour inside COREX shaft furnace.^{36,38)} For example, Hou *et al.* developed a DEM model to investigate the gas–solid flow in the reduction shaft of COREX, and investigated the effects of stickiness between particles and different shaft furnace geometry on the solid flow.^{36,37)} Zhou *et al.* developed a slot DEM model to simulate the macro- and microscope behaviours of solid flow in the shaft furnace with AGD under different conditions.³⁸⁾ However, these models only considered mono-size particles. As a result, some key features of solid flow in the shaft furnace such as particle size segregation caused by the AGD beams cannot be investigated.

In this work, a three-dimensional DEM-based model is developed to simulate the solid flow in COREX shaft furnace. The model is validated by comparing the simulations with measurements from physical experiments. The influences of AGD on solid flow in the shaft furnace including burden descending behaviour and particle segregation are investigated with considering four types of solids, including pellet, ore, flux and coke. Finally, several AGD beam arrangements are proposed and examined. The model is useful for the design, control and optimization of the shaft furnace of COREX.

2. Model Formulation

Each single particle in a considered system undergoes both translational and rotational motion, described by Newton's 2nd law of motion. The forces and torques considered include those originating from the particle's contact with neighbouring particles, walls and surrounding fluids. As the particles are densely packed and thus the gas flow has a minor effect on solid flow in COREX shaft furnace,^{23,24,36)} gas flow and its interaction with solid are not included in this study. The governing equations for translation and rotational motions of particle i with R_i , mass m_i and moment of inertia I_i can be written as

$$m_i(d\mathbf{v}_i)/dt = \sum_{j=1}^{k_i} (\mathbf{F}_{cn,ij} + \mathbf{F}_{dn,ij} + \mathbf{F}_{ct,ij} + \mathbf{F}_{dt,ij}) + m_i \mathbf{g}$$

$$I_i(d\omega_i)/dt = \sum_{j=1}^{k_i} (\mathbf{T}_{ij} + \mathbf{M}_{ij})$$

where, $\mathbf{v}_i$, ω_i represent translational velocity and rotational velocity of particle i , respectively. k_i denotes the particle numbers contacting with particle i . The forces involved are: the gravitational force $m_i \mathbf{g}$, and the contact force between particle and particle, which includes the normal and tangential contact forces $\mathbf{F}_{cn,ij}$ and $\mathbf{F}_{ct,ij}$, and damping forces in normal and tangential directions $\mathbf{F}_{dn,ij}$ and $\mathbf{F}_{dt,ij}$. In addition, the particle i bears two kinds of torque which are tangential

torque $\mathbf{T}_{ij}$ and rolling friction torque $\mathbf{M}_{ij}$.^{39–41)} All the forces and torques used in the model are listed in **Table 1**.

3. Simulation Conditions

The schematic diagram of the model setting used in this study is shown in **Fig. 1**. Case A is the shaft furnace without AGD beams. Case B is the shaft furnace with AGD beams. The model geometry of the shaft furnace used in the study is based on the actual size of a commercial COREX at Baosteel. The mixed burden of pellet, ore, flux and coke is charged from the top. The actual size of these solids varies considerably, and the average diameters of pellet, ore, flux and coke in plant operation are 13, 18, 28, 20 cm, respectively. In order to reduce the number of particles and hence the computational cost, three simplifications are made in the present work: (i) The particle diameters are enlarged by 7.5 times to reduce particle number considered and save computation time. Several groups of particles with different averaged diameters are used to represent the sizes of different burdens; (ii) Due to the plug flow zone typically in the upper part of shaft furnace,^{23,24,36,38)} the model does not consider the upper part of the shaft furnace; and (iii) The screw rotating speed in the simulation is accelerated. The simulation is started with the random generation of a certain number of well-mixed particles to form a packing bed in this model shaft furnace. Then the eight screws start to rotate at a pre-set rate to extrude the particles. When the burden surface passes through AGD beams, the simulation is stopped. **Table 2** lists the parameters used in the simulation.^{33,41,42)} The mass ratios and densities of different burdens are obtained from the plant operation in Baosteel.

Table 1. Forces and torques acting on particle i .

Forces and torques	Symbol	Equations
Normal contact force	$\mathbf{F}_{cn,ij}$	$-K_n \delta_n$ $K_n = \frac{4}{3} E^* \sqrt{R^* \delta_n }$
Normal damping force	$\mathbf{F}_{dn,ij}$	$-\eta_n V_{n,ij}$ $\eta_n = -2 \sqrt{\frac{5}{4}} \beta \sqrt{m^* K_n}$
Tangential contact force	$\mathbf{F}_{ct,ij}$	$-K_t \delta_t$ $K_t = 8 G^* \sqrt{R^* \delta_n }$
Tangential damping force	$\mathbf{F}_{dt,ij}$	$-\eta_t V_{t,ij}$ $\eta_t = -2 \sqrt{\frac{5}{6}} \beta \sqrt{m^* K_t}$
Torque arising from tangential forces	$\mathbf{M}_{t,ij}$	$R^* \mathbf{n} \times (\mathbf{F}_{ct,ij} + \mathbf{F}_{dt,ij})$
Rolling friction torque	$\mathbf{M}_{r,ij}$	$-\mu_r \mathbf{F}_{n,ij} \omega_{t,ij} / \omega_{r,ij} $

$$\text{where, } \frac{1}{E^*} = \frac{(1-\nu_i)^2}{E_i} + \frac{(1-\nu_j)^2}{E_j}, \quad \frac{1}{G^*} = \frac{2(2+\nu_i)(1-\nu_i)}{E_i} + \frac{2(2+\nu_j)(1-\nu_j)}{E_j},$$

$$\frac{1}{R^*} = \frac{1}{R_i} + \frac{1}{R_j}, \quad \frac{1}{m^*} = \frac{1}{m_i} + \frac{1}{m_j}, \quad \beta = \frac{\ln(e)}{\sqrt{\ln^2(e) + \pi^2}}, \quad \delta_n = [(R_i + R_j) - |\mathbf{x}_i - \mathbf{x}_j|] \mathbf{n},$$

$$V_{n,ij} = (\mathbf{V}_{ij} \cdot \mathbf{n}) \mathbf{n}, \quad V_{t,ij} = (\mathbf{V}_{ij} \times \mathbf{n}) \times \mathbf{n}, \quad V_{ij} = \mathbf{V}_j - \mathbf{V}_i + \omega_j \times \mathbf{R}_j - \omega_i \times \mathbf{R}_i, \quad \mathbf{n} = \frac{\mathbf{x}_j - \mathbf{x}_i}{|\mathbf{x}_j - \mathbf{x}_i|}$$

Note that the tangential forces ($\mathbf{F}_{ct,ij} + \mathbf{F}_{dt,ij}$) will be replaced by the maximum friction $-\mu_r |\mathbf{F}_{n,ij}| \omega_{t,ij} / |\omega_{r,ij}|$ when they are larger than the latter.

Fig. 1. Model settings used in the study: (a) Case A (shaft furnace without AGD), (b) Case B (shaft furnace with AGD) and (c) top view of Case B.

Table 2. Material properties and simulation parameters.

Parameters	Pellet	Ore	Coke	Flux	Wall
Density, ρ (kg/m ³)	3 425	4 760	1 100	2 800	7 850
Shear modulus, G (MPa)	10	10	2.2	10	79 000
Poisson's ratio, ν (–)	0.25	0.21	0.22	0.21	0.30
Diameter, d (cm)	10	13	21	15	–
Mass ratio (wt %)	51	34	7	8	–
Number of particles (–)	440 000	96 052	20 193	24 860	–
Restitution coefficient, e (–)	Pellet	0.2	0.3	0.3	0.5
	Ore	–	0.5	0.3	0.5
	Coke	–	–	0.5	0.5
	Flux	–	–	0.3	0.5
Static friction, μ_s (–)	Pellet	0.5	0.5	0.5	0.4
	Ore	–	0.5	0.5	0.4
	Coke	–	–	0.6	0.4
	Flux	–	–	0.5	0.4
Rolling friction, μ_r (–)	Pellet	0.02	0.05	0.05	0.05
	Ore	–	0.05	0.05	0.05
	Coke	–	–	0.05	0.05
	Flux	–	–	0.05	0.05
Time step, t (s)	5.8×10^{-4}				

4. Results and Discussion

4.1. Model Validation

The model is validated by means of comparing simulations (**Fig. 2(b)**) with measurements from physical experiments (**Fig. 2(a)**). The physical experiments are carried out using a semi-cylindrical setup. Corn grains are used to simulate burden materials. Figure 2(a) illustrates typical snapshots of burden profile in the physical experiment. The flow profile evolves from a flat-shape to wave-shape and finally to W-shape profile, as the solids descend. Figure 2(b) shows the calculated solid flow profile under the same condition used in **Fig. 2(a)**. The properties of corn particle, such as the Young's modulus, Poisson's ratio and coefficient of

restitution, are based on laboratory tests by Chung *et al.*⁴³⁾ The comparisons show a reasonable agreement between the calculated and measured solid flow profiles in aspects of both size and shape. The good agreement verifies the applicability of the present DEM model.

4.2. Effect of AGD on Burden Descending Velocity

In this paper, the vertical velocities of particles along y -direction are treated as burden descending velocity. The velocities averaged in the relatively stable period are used to represent the velocity at a given point. The particle's horizontal velocities (x -direction and z -direction component velocity) are ignored due to they are much smaller than vertical velocities. **Figure 3** shows the burden descending

Fig. 2. Comparison of burden profiles between simulations and experiments.

Fig. 3. Burden descending velocity along the central vertical planes in Case A and Case B.

Fig. 4. Triangle-shaped void below the AGD beam.

velocity of solid flow in the shaft furnace without AGD (Case A) and with AGD (Case B) along the vertical central plane. Figure 3(a) shows that in the upper part of the furnace, the relatively uniform descending velocity are observed in the radial direction. The maximum velocities are observed near the screws near the bottom, while the minimum velocities are observed below the gas slots, due to the enlarged cross-section area in this region. However, with the introduction of two AGD beams, the cross-section area varies significantly. It is shown in Fig. 3(b) that solid flow is more complicated, particularly around the beams, than that in the model without the AGD. The maximum burden descending velocities are observed below the AGD beams with a triangle shaped void generated. The relatively larger descending velocities are observed below the gap between the beams due to the compression of the effective furnace volume by the installation of AGD beams. On the contrary, slowly moving zones are observed at the upstream of the beams and near the walls at the lower part, which is different compared to those observed in Case A without AGD.

As an important feature of solid flow in shaft furnace with AGD installed, a triangle-shaped void is observed in the downstream of the beam in the simulation. The similar phenomenon is found in the previous experimental works,^{23,24)} as shown in Fig. 4. In the shaft furnace with

AGD, the reducing gas is blown into the furnace through the gas slots and AGD inlets, located in the bustle ring. As the triangle-shaped gas channels are generated below the beams, the reducing gas can flow from the AGD inlets into the shaft centre via the voids. This is the main reason that the reduction rate has been improved in the central part of the shaft furnace in practice. The schematic diagram of gas distribution through the AGD is shown in Fig. 5.

In order to have an overall understanding of the burden movements in the shaft furnace, four levels are used to characterise the burden descending velocity, at the height of 1.38 m, 4.5 m, 7.0 m and 9.5 m above the bottom, respectively. Figure 6 shows the burden descending velocity over the cross section at Level-4 (Height 9.5 m). It is indicated that the velocities in Case A are uniform and smaller than that in the centre part of Case B. The particles are moving slowly above the AGD beams due to the retardation of the installed AGD. Figure 7 shows the quantitative analyses of the burden descending velocity for the two cases in Level-4. In Case A, burdens have a relatively uniform descending in the peripheral direction, *i.e.*, from centre ($r/R=0.1$) to wall ($r/R=0.9$). On the other hand, in Case B with AGD installed, the solid flow become quite nonuniform in the peripheral region. The nonuniform distribution of the velocity may lead to the nonuniform distribution of residence time of burdens. As a result, such sluggish moving particles

Fig. 5. Schematic diagram of gas distribution around the AGD.

(a) Case A

(b) Case B

Fig. 6. Burden descending velocity in the cross section at Level-4 in Case A and Case B.

(a) 0.1 r/R

(b) 0.5 r/R

(c) 0.9 r/R

Fig. 7. Comparison of velocities along the peripheral direction in Case A and Case B.

(a) Case A

Level-1

Level-2

(b) Case B

Level-1

Level-2

Fig. 8. Burden descending velocity at Level-1 and Level-2 in Case A and Case B.

above the beams will have more chance to form scaffold.

Figure 8 shows the burden descending velocity at Level-1 (height=1.38 m) and Level-2 (height=4.5 m). It is indicated that the velocity distribution in Level-1 and Level-2 are quite similar in both Case A and Case B, expect for a slight higher velocity in Level-2 in Case B. Considering the burden descending velocities are uniform in the peripheral direction for both cases, the average of the velocities in the peripheral direction is calculated and used to present the velocity at a given radial direction, as illustrated in **Fig. 9**. At Level-1, the velocities evolution of Case A and Case B are quite similar, both reducing from centre to wall. At level-2, the average velocities of Case B are larger than that of Case A due to the initial larger velocity in bustle zone. They are both reducing from centre to wall. All these phenomena indicate that the AGD beams have a minor effect on the burden descending behaviour in the lower part of COREX shaft furnace.

Figure 10 shows the distribution of descending velocity at Level-3 (height 7.5 m), which is close to the lower edges of the bustle zone. The main difference between the two cases is that four relative low velocity regions are located below the AGD beams near the wall (inside the red circles) in Case B. This implies that the AGD beams can affect the solid flow throughout the bustle zone. In order to evaluate the difference quantitatively, two characteristic points located in $r/R=0.9$ position are selected, where Position-a

is located below the AGD beam and Position-b is located on the $x=0$ plane. **Figure 11** compares the descending velocities along the height at these two points between the two cases. At Position-a, the maximum velocity appears downstream of the beam due to the burden descending into the triangle-shaped void quickly by gravity. During descending, the descending velocities in Case B are smaller than that in Case A. However, at Position-b, the descending velocities in Case B are significantly larger than that in Case A when the height is over 600 cm. It is referred that after AGD installed (Case B), the burden in Position-a has more potential to increase the time of static contact and thus holdup. This is confirmed by our previous experimental study using a semi-cylindrical cold model. Detailed results are out of the scope of the present study and will be reported elsewhere.

4.3. Effect of AGD on Particle Segregation

As burden descending from the top and passing the AGD beams, the particles including pellet, ore, flux and coke may be redistributed. **Figure 12** shows the distribution of dif-

Fig. 9. Velocities along the radius direction in Case A and Case B.

Fig. 10. Burden descending velocity at Level-3 in Case A and Case B.

Fig. 11. Comparisons of the descending velocity along the height in Case A and Case B.

Fig. 12. Distribution of different size particles on $x=2$ m plane in Case A and Case B.

ferent size particles along the $x=2$ m plane in Case A and Case B. It can be seen that four types of burdens are nearly homogeneously mixing in Case A, while in Case B, the coke particles are accumulated below the AGD beams. This is because that as burden descending and passing the beams, a cavity is formed below the AGD beams (as shown in Fig. 4), and as expected, the void below the beams reaches the maximum. On the other hand, the movability of large particles, *e.g.* coke particle, is higher than that of small particles, that is, the large size particles are have more chance to roll into the cavity than the smaller particles, thus as a result the coke particle are accumulated below the AGD beams. The higher movability of coke particles can be confirmed in the previous studies on burden charging process where coke has a higher chance of segregating away from the striking point.^{44–47)}

The particle segregation is further analysed quantitatively in Fig. 13, showing the relation between normalized mass fraction of each particle, M_i/M_{i0} , and normalized radial distance r/R at different Levels in Case B. M_i is mass fractions of each particle size in a given radial position and M_{i0} is initial mass fractions of each particle size. The underlying mechanism is explored as: At Level-4, positioned above the AGD beams, it can be seen that, the M_i/M_{i0} values of large particles (flux and coke) are smaller than 1.0 in the middle part of $z=0$ plane, but the small particles (pellet and ore) are larger than 1.0 at that location. On $x=0$ plane at Level-4, each burdens are nearly homogeneously mixing along the radial direction. However, as burden passing the AGD beams, the particle segregation occurred. For the

normalized mass fraction distributes at Level-3 on the $z=0$ plane, as shown in Fig. 13(a), one can see that the M_i/M_{i0} value of flux and coke particles peaks at $r/R=0.5$ below the AGD beams, and less than 1.0 in the centre and wall of the shaft furnace. The small pellet and ore particles show the opposite tendency compared with the larger particles, *e.g.* coke. This result indicates that the large particles tend to move toward below the AGD beams due to the larger movability of large particles, *e.g.* coke, than that of small particles. Along the radial direction on $x=0$ plane, the M_i/M_{i0} values of flux and coke particles are smaller than 1.0, while the values of pellet and ore particles are larger than 1.0. This means that large particles have more chance to roll from centre to the location where AGD beams are installed. As burden continues to descend, the AGD beams have a minor effect on the burden descending velocity at the lower part, and hence, the normalized mass fraction distributes at Level-2 shows the similar tendency as shown in Level-3. However, it should be point out that, the higher density and smaller diameter of pellet and ore particles could lead to the percolation during descending, and the normalized mass fractions of pellet and ore in Level-2 are to a certain degree higher than that in Level-3. Level-1 is just located near the screw, detailed about the mass fraction of difference particles will be discussed later considering the mass fraction in the screw outlets.

The aforementioned particle segregation in the shaft furnace caused by the AGD beams will affect the gas distribution in the shaft furnace and thus likely the gas distribution in the followed MG. This is because the burden in the MG

Fig. 13. Normalized mass fraction as a function of normalized radial distance for different particle sizes at Level-2 in Case B, (a) $z=0$ plane, (b) $x=0$ plane.

is fed from the shaft furnace by eight screws, which are centrosymmetrically located at the bottom of the shaft furnace. As a result, the particle segregation in the shaft furnace will lead to the change of mass fraction of difference particles in these screw outlets. **Figure 14** compares the average mass fraction of each material at No. 2 outlet between Case A and Case B. The No. 2 outlet is located right below the AGD beam, as shown in Fig. 1. It can be seen that the mass fraction of flux and coke are larger than that in Case A. Specifically, the fraction of coke in case B increases by 10.44% compared with that of Case A. While for the mass fraction of pellet and ore, they are smaller than that in Case A. These results are consistent with the phenomenon as discussed in Fig. 12.

Figure 15 shows the mass fraction of each material at difference outlets in Case B. It is indicated that the normalized mass fractions of coke and flux are larger in No. 2 outlet but smaller in No. 1 and No. 3 outlets, whereas that of pellet and ore are smaller in No. 2 and larger than 1.0 in No. 1 and No. 3 outlets. This implies that aiming to achieve reasonable burden distribution in MG, the charging strategy through these outlets should be adjusted. For instance, the burden discharging from No. 1 and No. 3 outlets where more small particles are discharged, should be discharged to the periphery for protecting the lining, whereas the large particles from No. 2 outlet can be discharged to the centre for developing central gas flow.

Fig. 14. Comparisons of mass fraction of each material at No. 2 outlet in Case A and Case B.

4.4. Optimization of AGD Arrangements

In this work, several new arrangements of AGD beams are proposed. They are illustrated in **Fig. 16**: Case C is single span beam, Case D and Case E are three and four spoke beams, respectively (*i.e.* the beam length is 3 m long and the angel between two beams are 120° and 90°, respectively).

Figure 17 shows the burden descending velocity at Level-4 for these AGD arrangements *i.e.* Cases C, D, and E. In the cases, the particles are moving slowly above the beams. The average burden descending velocity is increasingly higher from Case C to Case E, as more flow-effective furnace volume is occupied by the AGD beams. **Figure 18** shows the velocities distribution along the peripheral direction in Cases, C, D and E. It is indicated that these AGD arrangement will affect the solid flow in the peripheral direction as well. For example, the homogeneity of velocity profile along the peripheral direction in Cases C–E is better than that in Case B due the symmetrical arrangement of AGD in Cases C–E. Specifically, the standard deviation of the velocity in Cases C, D and E decrease by 35.7%, 33% and 15.7% respectively, compared with that of Case B. As of uniform distribution of velocities, the new arrangement of AGD has less effect on the uniform flow of solids in bustle zone, especially for Cases C and D. On the other hand, considering installation, maintenance and replacement of the AGD beams, Cases D and E are more convenient options compared to Cases B and C. Thus, Case D is finally regarded as the optimal arrangement in this work in aspects of its less effect on uniform burden descending and its more convenient engineering practice. It is worth

Fig. 15. Comparisons of mass fraction of each material at different outlets in Case B.

Fig. 16. Schematic diagrams of different AGD beam designs.

Fig. 17. Cross-section (perpendicular to the y axis) of velocity distribution at Level-4 in Cases C–E.

Fig. 18. Burden descending velocities along the peripheral direction in Cases C–E.

Fig. 19. Effects of AGD designs on mass fraction of coke at different outlets.

noting that the burden descending behaviour is only one of the important aspects of production performance. In order to attain a comprehensive understanding of the overall effect of AGD arrangements on the shaft furnace performance, the gas distribution and top gas utilization, as well as the metallization rate, should be taken into account and reported elsewhere.

Figure 19 shows the effects of these AGD arrangements on coke mass fraction at different outlets. The simulations indicate that the normalized mass fraction of coke at the outlet located far away from the AGD beams (e.g. No. 1 outlet in Case C, No. 2 outlet in Cases D and E), are close to

1.0, whereas the outlets located right below the AGD beam have a value much greater than 1.0.

5. Conclusions

In this work, a three-dimensional DEM-based model is developed for simulating the solid flow in the shaft furnace of COREX. The model was validated by the good agreements between the simulation and experiment. The effect of AGD and its arrangement on burden descending velocity and material size segregation were discussed. The following conclusions can be drawn from the present study.

(1) COREX shaft furnace without AGD experiences a relatively uniform solid descending across the radial direction in the bustle zone. However in the shaft furnace with AGD installed, the largest burden descending velocities are observed below the AGD beams where a triangle-shaped void is generated, and the slowly moving zones are observed above the beams.

(2) The AGD beams can affect the solid flow significantly in the bustle zone but slightly in the lower part of COREX shaft furnace. The triangle-shaped void below the AGD beams allows the reducing gas flowing into the shaft centre.

(3) The more coke and flux particles roll toward below the AGD beams, and thus the normalized mass fractions of coke and flux are larger than 1.0 in the screw outlet located right below the AGD beams. This indicates that MG will have more options in burden charging. For instance, the

burden discharging from the screw outlets with more large cokes can be charged to the centre for developing gas flow distribution at the centre of MG.

(4) Three new arrangements of AGD beams are proposed and examined in this work. The case with three AGD beams (*i.e.*, the length is 3 m and the angle between two beams is 120°) is regarded as the optimal arrangement for uniform burden descending and convenient engineering practice.

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