Research Article

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A downscaling cold model for solid flow behaviour in a top gas recycling-oxygen blast furnace

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Abstract: The top gas recycling-oxygen blast furnace (TGR-OBF) is a reasonable method used to reduce both coke rate and energy consumption in the steel industry. An important feature of this process is shaft gas injection. This article presents an experimental study on the gas–solid flow characteristics in a TGR-OBF using a two-dimensional cold model. The experimental conditions and parameters were determined using a series of similarity criteria. The results showed that the whole flow area in the TGR-OBF can be divided into four distinct flow zones, namely, the stagnant zone, the plug flow zone in the upper part of the shaft, the converging flow zone and the quasi-stagnant flow zone, which is similar to that in a traditional blast furnace. Then the effects of batch weight and the ratio (X) of the shaft injected gas flow rate to the total gas flow rate on solid flow behaviour were investigated in detail. With the increase in batch weight, the shape of the stagnant zone tends to be shorter and thicker. Furthermore, with the increase in X value from 0 to 1, the stagnant zone gradually becomes thinner and higher. The results obtained from the experiments provide fundamental data and a validation for the discrete element method–computational fluid dynamics–coupled mathematical model for TGR-OBFs for future studies.

Keywords: top gas recycling-oxygen blast furnace, cold model, shaft gas injection, solid flow

1 Introduction

According to the International Energy Agency [1], the iron and steel sector accounts for about 5% of the total global CO₂ emissions. A reduction in CO₂ emissions in the iron and steel industry, especially in the iron-making process, has emerged as a serious subject in slowing down the rate of global warming [2]. The mainstream view [3] of improving the energy efficiency of the iron-making process entails the ideas of low-temperature operation, the development of hydrogen reduction, a decrease in the energy used for reducing iron oxides, the effective use of carbonaceous materials and the development of new processes.

The production of blast furnace (BF) cannot be separated from coke, which is used as a fuel reduction and stock column. However, due to the shortage of coke resources, high price and large production investment, coke is an immediate issue to be solved in the iron and steel industry [4,5]. Therefore, a top gas recycling-oxygen blast furnace (TGR-OBF) is considered to be a favourable way to remarkably decrease the rate of coking [6]. The TGR-OBF replaces the traditional preheating air blast by adopting oxygen blasting [7–9]. CO₂ is removed and returned to the BF for re-utilization. The TGR-OBF has the advantages of high productivity, low coke ratio and high calorific value of gas.

In this regard, some joint projects have resulted in related industrial experiments, including ultra-low CO₂ steelmaking in Europe [10–12] and experimental OBFs in Japan [13,14] and Russia [10]. The main characteristics or advantages [11] of OBF-based iron-making processes include top gas recycling, shaft gas injection, a low rate of coking, a high rate of injection of pulverized coal and a high utilization coefficient. However, due to the fact that the BF is a complex multiphase (gases, solids, liquids and powders) flow system [15,16], any improvements in the design must maintain its stable operation. In particular, to

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further study the improvement in the BF design, it is necessary to investigate the influence of shaft gas injection, decreasing the blast volume in hearth tuyere and increasing the utilization coefficient on the BF design.

Over the past few decades, gas–solid or gas–solid–liquid flows in a traditional blast furnace (TBF) have been extensively investigated using physical modelling, which involved two-dimensional (2D) [17–19] or three-dimensional (3D) [17,20,21] downscaling BF or COREX models. These studies have led to various findings, which are briefly summarized here. First, four flow regions were identified in a TBF solid flow [17], namely, the plug flow, the stagnant zone, the quasi-stagnant zone and the converging flow zone. Second, Takahashi and Komatsu [22] and Wright *et al.* [17] reported that the stagnant zone increased with a decrease in the solid flow rate or an increase in the gas flow rate. The mathematical analysis of solid flow in the BF or COREX is divided into three categories, namely, the continuous model [23], the discrete model [24–26] and the discrete–continuous model [27]. Furthermore, Zhang *et al.* [28] used the unsteady model to demonstrate the typical unsteady analyses of the TGR-OBF processes. They found that under the default condition, it takes about six times for the main gas elements travelling from the tuyere zone to the furnace top, until the unsteady process becomes stable. In addition, the exergy analyses of the TBF and two kinds of TGR-OBF with different oxygen enrichment were carried out [29]. Compared to the TBF process, carbon consumptions by two kinds of TGR-OBF processes decrease by 14.1% and 20.2% based on default conditions. Using numerical simulation, Helle *et al.* [30] studied the pure oxygen that is used as blast combined with recycling of CO₂-stripped top gas. The research results provided a reference for evaluating the feasibility of operating the BF under high top gas recycling rates. However, only a handful of studies [17,22] analysed the influence of shaft gas injection on descending burden behaviours in the TGR-OBF. Furthermore, the gas injection from shaft tuyeres plays an important role in increasing the shaft reduction potential and making up the heat balance in the upper part. Therefore, it is necessary to study the effect of shaft injected gas (SIG) on the descending burden behaviour in a BF. In this study, the solid flow behaviour in the furnace was investigated using a 2D slot physical model. The effects of different variables, including batch weight and SIG flow rate, were specifically examined. The study is expected to provide basic data for the development of this process and also serves as a good validation case for the future DEM-CFD simulation study

2 Experimental

2.1 Apparatus

Figure 1 shows the schematic of the 2D slot model (in a 1:10 ratio) used in the experiments. The model shape was based on TGR-OBF, which is planned to be constructed in China. The geometrical parameters of TGR-OBF are summarized in Table 1. The model has two transparent organic glass walls, forming the front and rear surfaces with a pitch of 50 mm. The whole model consisted of a gas supply system, the TGR-OBF, a screw discharging system and a closed silo box. Furthermore, three hearth and shaft tuyeres, each 8 mm in inner diameter, were attached to each side wall to ensure uniformity of gas in the model along the direction of the thickness [19]. The tuyeres had a distance of 0 mm from the inner surface of the wall. The coke consumption in the raceway of the BF was simulated by discharging particles from a pipe of 40 mm inner diameter, which was attached to the front surface at an angle of 45° [18]. The extraction rate of particles was controlled using screw discharging installed in the closed silo box, which was connected with a deceleration motor. Nitrogen (N₂) was supplied at room temperature from a gas cylinder through a pressure regulator, which ensured that the gas pressure of each tuyere was uniform. Four rotor flow meters were used to control the gas flow rate from each tuyere. N₂ ascended through the apparatus, exited from the top of the bed and was released into the atmosphere. Since the discharged particles from the model were stored in a closed particle collector, the gas leakage from the lower part of the model could be avoided. The particles in the model were mung beans and alumina spheres with a uniform diameter, which were simulated coke and ore, respectively. The physical properties of the particles are presented in Table 2.

2.2 Methodology

At the start of each experiment, the particles were packed to form uniform horizontal layers. The white alumina layers (spherical particles) were alternated with the layers of green mung bean particles, as shown in Figure 2(a). After finishing the packing, N₂ was pumped into the system. The particles were discharged at the same time. The solid particles were manually fed to maintain a constant height at the top of the bed. When

Figure 1: A schematic diagram of the two-dimensional (2D) cold model.

the amount of exhaust particles equalled with the initial amount of the filling particles, the solid flow attained steady state. Then the boundary between the initial filling particles (stagnant region or dead man) and the added particles (flowing region) was determined. One red ball in burden was set as the tracked particle. The timeline and streamline can be obtained by varying the position at different times. The initial state and steady state are shown in Figure 2. Then the characteristics of

the flowing region were analysed, marking the end of the experiment.

The two important parameters, namely, the gas and solid flow rates, are determined based on the modified Froude number at the throat region of the BF. The modified Froude number, Fr , is represented using Equations (1) and (2) and relates the inertial forces acting on a phase to the gravitational forces for both the solid and gas phases [20].

Table 1: The geometric parameters of this model

Hearth height/mm	Bosh height/mm	Belly height/mm	Shaft height/mm	Throat height/mm	Hearth diameter/mm
320	239	80	496	150	320
Belly diameter/mm	Throat diameter/mm	Hearth tuyere height/mm	Shaft tuyere height/mm	Stack angle/°	Bosh angle/°
400	300	272	272	84.3	80.5

Table 2: The physical properties of the two particles used in this study

Material	Diameter (d_p)/mm	Bulk density (ρ_s)/kg m ⁻³	Internal angle of friction/°
Mung bean	4.5	810	25
Alumina sphere	1.5	600	35

Figure 2: The state of the burden: (a) initial state and (b) steady state.

$$Fr_s = \frac{\rho_g}{\bar{\rho}_s - \rho_g} \cdot \frac{U_s^2}{g\bar{d}_p} \quad (1)$$

$$Fr_g = \frac{\rho_g}{\bar{\rho}_s - \rho_g} \cdot \frac{U_g^2}{g\bar{d}_p} \quad (2)$$

where U_s is the linear velocity of the particles at the throat of the furnace (m/s), U_g is the gas superficial velocity at the throat of the furnace (m/s), $\bar{\rho}_s$ is the average bulk density of the particles (kg/m^3), ρ_g is the gas (nitrogen) density (1.25 kg/m^3), g is the local acceleration of gravity (9.8 m/s^2) and $\bar{d}_p$ is the average particle diameter (m).

In the actual BF operation, the Froude number for solid flow is in the order of 10^{-8} to 10^{-9} [31], whereas the Froude number for gas flow is in the order of 10^{-3} to 10^{-4} [17]. In this study, the Froude number for solid flow is set as 4.5×10^{-9} . According to the data in Table 1, $\bar{\rho}_s$, ρ_g and $\bar{d}_p$, we can obtain the solid descent velocity of around 1.75 cm/min at the throat using Equation (1). In the same method, when the Froude number for gas was set as 7.6×10^{-4} , the gas superficial velocity was 0.13 m/s at the top. The details of the experimental conditions in the 2D slot model are listed in Table 3. Nine different cases were designed. Cases 1, 2 and 3 were designed as a basic test to study the influence of interface layer numbers on the movement characteristics of burden. Considering the ore and coke batches in the actual BF, the interfacial layer numbers were set to investigate the gas–solid two-phase flow. In addition, the hearth tuyere flow rate and the shaft tuyere flow rate were investigated to discuss the influence of different blast volumes on the

Table 3: Experimental conditions

Case	Interface layer numbers	Hearth tuyere flow rate (Nm^3/h)	Shaft tuyere flow rate (Nm^3/h)	Throat particle velocity (cm/min)
1	16	0	0	1.7–1.8
2	8	0	0	1.7–1.8
3	4	0	0	1.7–1.8
4	8	20	0	1.7–1.8
5	8	14	6	1.7–1.8
6	8	10	10	1.7–1.8
7	8	0	20	1.7–1.8
8	—	20	0	—
9	—	0	20	—

gas–solid movement. The ratio of the SIG flow rate to the total gas flow rate is defined as X .

The solid descent driving force in the actual BF is mainly caused by the following factors: coke combustion in the raceway, coke consumption in the direct reduction and carburization process, iron ore melting in the cohesive zone, periodic discharge of iron/slag and the mixing of small particles with bulk particles. Apart from coke combustion and periodic discharge of iron/slag, all other factors are usually insignificant. In this study, the experimental procedure was specifically designed for the iron-making cycle; as a result, there is no need necessity to consider iron/slag discharge. In addition, the melting of iron ore will increase the descent velocity of solid flow above the cohesive region. However, it does not affect the flow pattern below the cohesive region [32]. Therefore, in this study, similar to many other experimental studies [17], only the coke combustion in the raceway is considered as the main driving force for solid.

3 Results and discussion

3.1 Internal flow structure in the TGR-OBF

Under different conditions, the movement of the burden reached a steady state after 50 min. Meanwhile, the change in the stagnant zone was not obvious. Figure 3 shows the burden movement region under the TGR-OBF (with a hearth tuyere flow rate of $14 \text{ Nm}^3/\text{h}$ and a shaft tuyere flow rate of $6 \text{ Nm}^3/\text{h}$) conditions in Case 5 after 50 min. The whole flow area was divided into four distinct flow regions in the TGR-OBF case. The most

Figure 3: The steady state of the particles under TGR-OBF conditions in Case 5 (time: 50 min): (1) the plug flow zone, (2) the quasi-stagnant zone, (3) the stagnant zone and (4) the funnel flow zone.

important flow region was the conical stagnant zone (Zone 3), which was formed in the lower part of the furnace hearth and expanded from the hearth tuyere

level. The particles in this area exhibited no obvious flow behaviour, although the shape of this area showed a significant influence on the flow state of other areas. The quasi-stagnant zone (Zone 2) was located at the surface of the stagnant zone. The particles move slowly and disorderly; as a result, the mixing phenomenon of the two kinds of particles is shown in Figure 3. The converging flow zone (Zone 4) was near the wall of the belly and bosh, and above the raceway, and was mainly located between the quasi-stagnant zone and the furnace wall. The particles in this region have the fastest descent velocity because of the extrusion from the stagnant zone. The funnel flow region (Zone 1) refers to the zone between the upper part of the shaft and the stock line. The particles in this region had a similar descent velocity at a certain height, except near the furnace wall, where they descended slowly because of the friction. The particle flow region in the TGR-OBF exhibited four sub-regions, which were similar to the TBF derived from the cold model [17,22]. Some previous studies [33] indicated that the burden descent velocity was basically dependent on the furnace profile and melting zone shape. Compared with the TBF, the solid flow characteristics in TGR-OBF did not change substantially. The stagnant zone obtained from the 2D model was larger than that of the 3D model [17], which was due to the friction between the particles and the front-rear wall. However, the solid flow characteristics in the furnace can still be captured.

Figure 4 shows the change in the burden flow structure over time in the TGR-OBF in Case 5. The particles in the furnace exhibited the following changes during the descending process: during the 0–10 min period, the particles at the furnace throat were first unstable and did not descend evenly in the radial

Figure 4: The internal flow structure change over time under TGR-OBF conditions in Case 5.

direction. The particles near the wall descended faster than those at the centre. This was mainly due to the fact that there was no stable stagnant zone at the bottom centre of the furnace. After 10 min into the stabilizing process of the stagnant zone, the descent velocity of the particles in the upper part of the shaft gradually became the same, except those near the wall, which had a slower descent velocity due to friction with the side wall.

3.2 Effect of batch weight on solid flow behaviour

In an actual BF, the number of interfacial layers of the burden changes with a change in the charge of the bell-less top. The steady state of the particle motion in the furnace is shown in Figure 5 for Cases 1, 2 and 3. Figure 5(a) shows the experimental results for different cases after 54 min. Figure 5(b) shows the change in timelines and streamlines over time.

Figure 5 shows that with the decrease in the number of interfacial layers, the height of the stagnation zone gradually decreases, and the diameter gradually increases. From Cases 1 to 3, the height of the stagnation zone gradually decreased from about 32 to 26 cm. In addition, the diameter of the stagnation zone increased from about 8 to 12 cm at the same time. However, for different cases, the burden motion characteristics in the upper part of the shaft (plug flow zone) barely changed for the same descent velocity. Furthermore, the burden motion characteristics in the bosh (converging flow zone) changed a great deal, while the burden descent velocity decreased with an increase in the initial number of interfacial layers. The quasi-stagnant zone at the surface of the stagnant zone changed with a change in deadman. For example, the 40.5 min timelines showed a tendency to move up, which was mainly due to the difference in the particle sizes between the ore (alumina spheres) and the coke particles (mung beans). During the descending process, two kinds of particles were mixed with each other, which led to an increase in the inner friction and the stacking angle of the mixed particles. The more the batches, the more uniformly mixed were the ore and coke particles and the larger the inner friction. Owing to these features, the particles in the quasi-stagnant zone moved steadily and played a supporting function for the height of the stagnant zone. Finally, the flow characteristics of the funnel flow region changed. The results showed that, in addition to the smelting intensity, the form of the stagnant zone also

had a great influence on burden movement. Therefore, the charge pattern exhibited a significant influence on the form of the stagnant zone and the descending pattern of the burden.

3.3 Effect of ratio (X) on solid flow behaviour

It is worth mentioning that there was an additional row of shaft tuyeres at the bottom of the TGR-OBF shaft and that the SIG flow rate differed for different process conditions. Therefore, in this section, the effect of X value on the movement characteristics of the burden was investigated. The results are shown in Figure 6. In the furnace, the total gas flow rate was kept the same under different conditions, whereas the X values varied successively through 0, 0.3, 0.5 and 1. Additionally, the particles' descent velocities at the furnace throat remained unchanged.

Figure 6 shows that the airflow had no effect on the particles' descending behaviours in the plug flow zone in the upper part of the shaft. However, under this flow region, Cases 2 (no gas flow condition) and 4 (TBF condition, with a hearth tuyere gas flow rate of 20 m³/h) were compared. After the hearth tuyere injecting gas, it can be clearly seen that the stagnant zone expanded, which is in accordance with the results reported in previous studies [17]. Then Cases 4, 5, 6 and 7, representing the TGR-OBF conditions with the shaft gas injected, were compared. When the proportion of SIG increased from 0 to 1 from Cases 4 to 7, the stagnant zone gradually became thinner and higher. At the same time, the descending behaviour of particles above the central axis of the stagnant zone became limited. The middle part of the 25 min timeline had an obvious upward trend because of the reduction in descent velocity. On the contrary, with the increase in SIG proportion, the descent velocity of the particles belonging to the funnel flow region (close to the bosh wall) increased. When the proportion increased to 1, the descent velocity of the particles near the upper part of the bosh wall significantly slowed down because of the buoyancy of SIG. The 31.25 min timeline close to the bosh wall became deformed for Case 7. It should be noted that Case 7 cannot appear in the actual TGR-OBF. The shape of the stagnant zone was affected not only by the SIG proportion but also by the shape of the cohesive zone. Some previous studies [34] showed that the position of the cohesive zone became lower, thinner or even

Figure 5: The steady state of the burden movement in experiment (a) and the schematic diagram of the timelines and streamlines of the burden (b).

Case 2($X=0$) Case 4($X=0/10$) Case 5($X=3/10$) Case 6($X=5/10$) Case 7($X=10/10$)

(a)

Case 2($X=0$) Case 4($X=0/10$) Case 5($X=3/10$) Case 6($X=5/10$) Case 7($X=10/10$)

(b)

Figure 6: The effect of SIG flow rate on the burden steady state in the experiment (a) and the schematic diagram of the timelines and streamlines of the burden (b).

disappeared under TGR-OBF conditions. Therefore, through the current cold model and without the consideration of the cohesive zone, it can be considered that the SIG had a more significant effect on the shape of the stagnant zone than the hearth injected gas.

4 Conclusions

In this study, according to the similarity theorem, a downscaling cold model is established for the TGR-OBF. The solid flow behaviour under different conditions was studied, especially in the TGR-OBF. Various influencing factors, such as the batch weight and the SIG flow rate, were studied. The research results can be summarized as follows.

- (1) The solid flow characteristics in the TGR-OBF are consistent with those in the TBF and can be divided into four zones, namely, the stagnant zone, the funnel flow zone, the converging flow zone and the quasi-stagnant zone. However, the 2D model cannot eliminate the significant influence of the wall effect on the shape of the stagnant zone and the flow mode of the particles.
- (2) Batch weight has a significant influence on the descending burden behaviour. With the increase in batch weight, the shape of the stagnant zone tends to become shorter and thicker. At the same time, under the influence of the changing stagnant zone, the converging flow zone and the quasi-stagnant zone also change. However, it has little impact on the plug flow zone in the upper part of the shaft under different conditions.
- (3) By increasing the X value from 0 to 1, the stagnant zone gradually becomes thinner and higher. The SIG has more significant effect on the shape of the stagnant zone than the hearth injected gas under the TGR-OBF condition, which has a thinner cohesive zone.

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