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NUMERICAL SIMULATION ON DYNAMIC AND STATIC HOLDUPS OF POWDER INSIDE PRE-REDUCTION SHAFT FURNACE[1]

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Abstract

In some non-blast furnace ironmaking processes, such as COREX smelting reduction process, the reducing gas, introduced into the upper pre-reduction shaft furnace, usually contains a considerable quantity of dust or powder as a result of coal gasification and iron-bearing burden decomposition in melter gasifier, and the powder distribution behaviors make direct and important influences on gas flow as well as burden reduction inside pre-reduction shaft furnace. Based on momentum exchange among gas-solid-powder phases and empirical equations, a two-dimensional mathematical model was established in the present work to simulate both dynamic and static holdups of powder. There were two blockade zones existing in the centre and edge regions near the bottom respectively. The dynamic holdup of powder firstly increased to 3.0e-3 and then decreased to 7.0e-4 as the gas ascended from the inlet to the top. At the bottom of the shaft furnace, the relatively low gas velocity gave rise to dynamic powder accumulation. By contrast, the static holdup of powder generally increased from 2.0e-5 near the edge to as high as 1.8e-4 near the centre at the gas inlet level and the trend was further promoted to 5.0e-3 in the central inactive zone or even to 1.0e-1 at the bottom below the gas inlet. In addition, the influences of the powder density, the feed rate and the man-made deadman shape on powder distribution behaviors inside pre-reduction shaft furnace were also investigated in this work.

Key words: Mathematical model; Powder phase; Holdup distribution; Pre-reduction shaft furnace.

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1 INTRODUCTION

The research on powder or fine distribution behaviors inside blast furnace, caused by unburned char or fine coke especially under high PCI, has been a popular subject in the ironmaking field. After a one-dimensional cold model was used to investigate the pressure loss caused by the increase in the holdup of powder,[1] two-dimensional physical and mathematical models were developed to determine the effect of powder on the pressure loss and other blast furnace operations.[2-4] The ascending velocity of powder was also measured by bifurcated optical probe.[5-6] The relationship between powder holdup and coarse or fine particle diameter as well as density were clarified by experiments and described by a proposed momentum balance model.[7-8] Furthermore, the whole holdup of powder were studied by using separate treatment of dynamic and static holdup,[9] and the related mathematical model of blast furnace were developed under either stable or transient state based on the multi-fluid theory.[10-12] As for some non-blast furnace ironmaking processes without cohesive zone, around which the powder distribution behaviors were simulated inside blast furnace,[13-14] the accumulation of powder formed blockade inside shaft furnace, thus causing burden hanging problems.[15-17] Due to the fact that coal plays an increasingly important role as a reducing agent than coke in the non-blast furnace ironmaking process in terms of cost efficiency and environment concerns, the quantity of powder contained in the generated gas was greater, making a much more negative effect on gas flow distribution and iron oxide reduction inside shaft furnace than that inside blast furnace. What's more, the decomposition of iron-bearing burden or direct reduced iron in melter gasifier increased not only the quantity but also the density of powder. In addition, the structure of shaft furnace, especially the profile design of the man-made deadman also affected the powder distribution behaviors. As a whole, due to above reasons, it was of great importance to study both the dynamic and static holdups of powder inside the pre-reduction shaft furnace.
Since in previous work, the influences of injection parameters, such as location, diameter and inclination angle of the injection pipe, on the inner pre-reduction shaft furnace features were studied based on a simplified two-dimensional mathematical model,[18] the present work further investigated both dynamic and static holdup distributions of the powder inside pre-reduction shaft furnace by using an improved model consisting of gas-solid-powder multi-phases. Meanwhile, the influences of the powder density, the feed rate and the shape of man-made deadman on above behaviors were also studied.

2 MODEL FORMULATION

The general conservation equations of continuity and momentum for gas, solid and powder phases in steady state could be described by Equation 1.[19]

$$\nabla(\varepsilon_p \cdot \rho_p \cdot \phi \cdot \vec{v}_p) = \nabla(\varepsilon_p \cdot \Gamma_\phi \cdot \nabla(\phi)) + S_\phi \qquad (1)$$

The detailed explanations of the variables in Equation 1 were summarized in our previous works.[20-21] It was worth noting that in the present work, the dynamic powder was taken as a fluid phase while the static powder was defined as a discrete phase not moving against the solid, which meant that the static powder holdup directly contributed to the solid volume fraction. Besides, the interphase exchange coefficients among the three phases were clarified in Table 1.

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Table 1. Interphase exchange coefficients among gas-solid-powder phases

Term	Expressions	Reference
Gas-Solid	$150\dfrac{\varepsilon_s(1-\varepsilon_g)\mu_g}{\varepsilon_g d_s^2}+1.75\dfrac{\rho_g\varepsilon_s\lvert\vec{v}_s-\vec{v}_g\rvert}{d_s}$	[22]
Gas-Powder	$\dfrac{3}{4}C_D\dfrac{\varepsilon_p\varepsilon_g\rho_g\lvert\vec{v}_p-\vec{v}_g\rvert}{d_s}\varepsilon_g^{-2.65}$	[23]
Solid-Powder	$\dfrac{1}{2D}\rho_p\varepsilon_p\lvert\vec{v}_p-\vec{v}_s\rvert f_p(\vec{v}_p-\vec{v}_s)$	[4]

The two-dimensional model was axial symmetry, so only half schematic diagram was shown in Figure 1. The densities of gas, solid and powder were 1,225 kg/m^3, 2,150 kg/m^3 and 2,500 kg/m^3 and their viscosities were 1.8e-5, 6.0 and 0.8 kg/(m·s) respectively. The initial powder volume fraction at gas inlet was 1.0e-5 with the gas velocity equal to 20.0 m/s. The solid was charged from top with the velocity of 8.0e-4 m/s and the volume fraction was set 0.6 and distributed uniformly. The dynamic and static holdups of powder were both determined by introducing the empirical equations proposed by HIDAKA.[9]

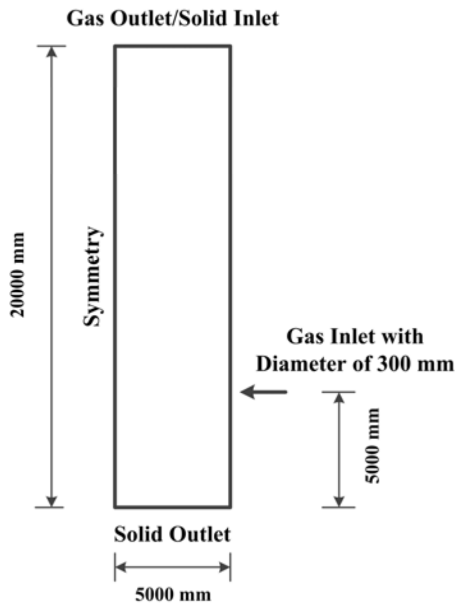

Figure 1. Schematic diagram of two-dimensional model.

3 RESULTS AND DISCUSSION

3.1 Basic Characteristics of Powder Distribution

The dynamic and static holdup distributions of the powder inside the furnace were demonstrated in Figure 2. It could be found that the two holdup distributions were similar around and above the inlet level, but the specific values of the dynamic holdup were much greater than those of the static holdup as a result of the high gas velocity. By contrast, at the bottom of the furnace, due to the low gas velocity, the dynamic holdup decreased to as low as 1.0e-5 when most powder deposited on the solid surface, so there were two blockade zones located at the corner near the furnace wall and centre respectively as shown in Figure 2b with the value above 5.0e-3 in the central inactive zone or even to 1.0e-1 at the bottom below the gas inlet. Two

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horizontal levels, 5 m and 15 m above the bottom, were selected in order to further analyze above behaviors with the results shown in Figure 3.

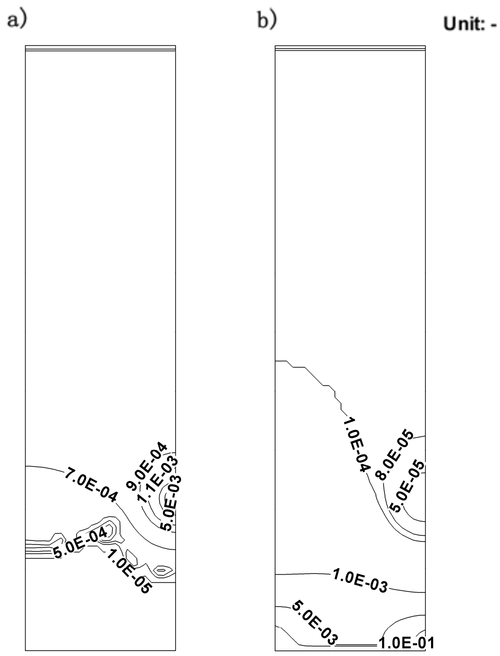

Figure 2. The (a) dynamic and (b) static holdup distributions of powder inside furnace.

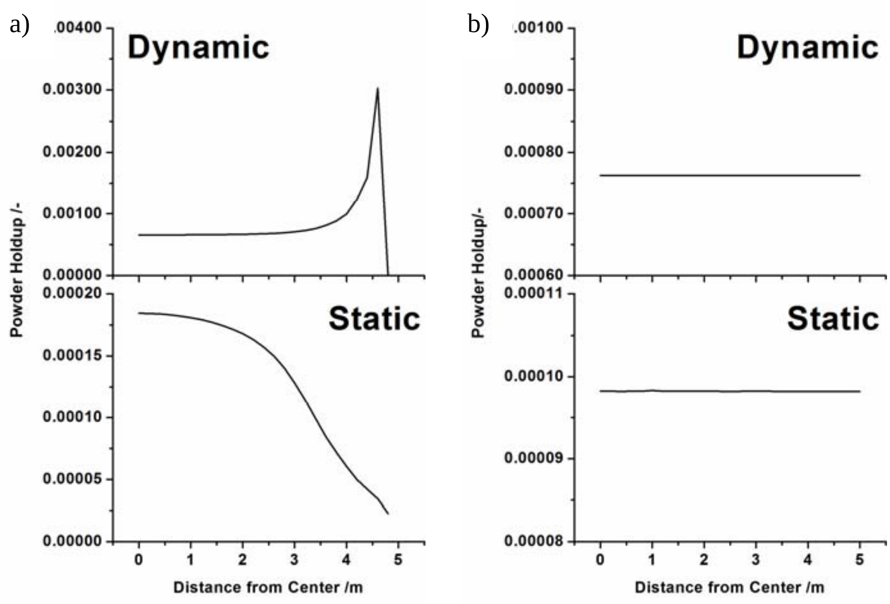

Figure 3. The dynamic and static holdup distributions of powder at two horizontal levels: (a) 5 m and (b) 15 m height from bottom.

Since the gas inlet was located at 5 m high from the bottom, the powder holdup distributions were strongly affected by the gas flow. In Figure 3a, as the direction of gas flow changed from centreward to upward, the powder dynamic holdup increased sharply, the greatest value being about 3.0e-3 located 0.5 m away from the inlet, and then decreased with great gradient to 7.0e-4. As for the powder static holdup, the high gas velocity near the inlet left the static powder accumulating at the centre and

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the bottom. The values increased from 2.0e-5 near the edge to as high as 1.8e-4 near the centre at the gas inlet level. Since the height increased from the inlet level to the upper part, both holdup distributions become stable in radical direction and most powder existed in the motion state.

3.2 Influence of Powder Density on Its Distribution

In this section, with the powder density varing from 1,500 to 3,500 kg/m^3 with the interval of 500 kg/m^3, the powder dynamic and static holdup distributions were compared in Figures 4 and 5 respectively.

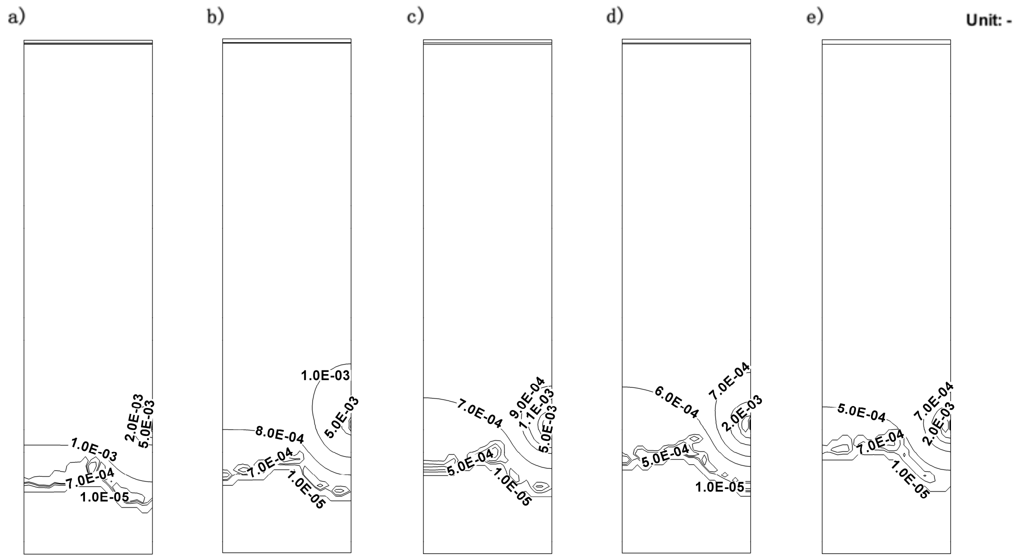

Figure 4. The effect of powder density on its dynamic holdup inside furnace: (a) 1,500 kg/m^3; (b) 2,000 kg/m^3; (c) 2,500 kg/m^3; (d) 3,000 kg/m^3; (e) 3,500 kg/m^3

From Figure 4, it could be found that the increase of the powder density generally reduced its dynamic holdup in most part inside the furnace except near the bottom. By contrast, the powder static distribution was not affected by the variation of the powder density as shown in Figure 5.

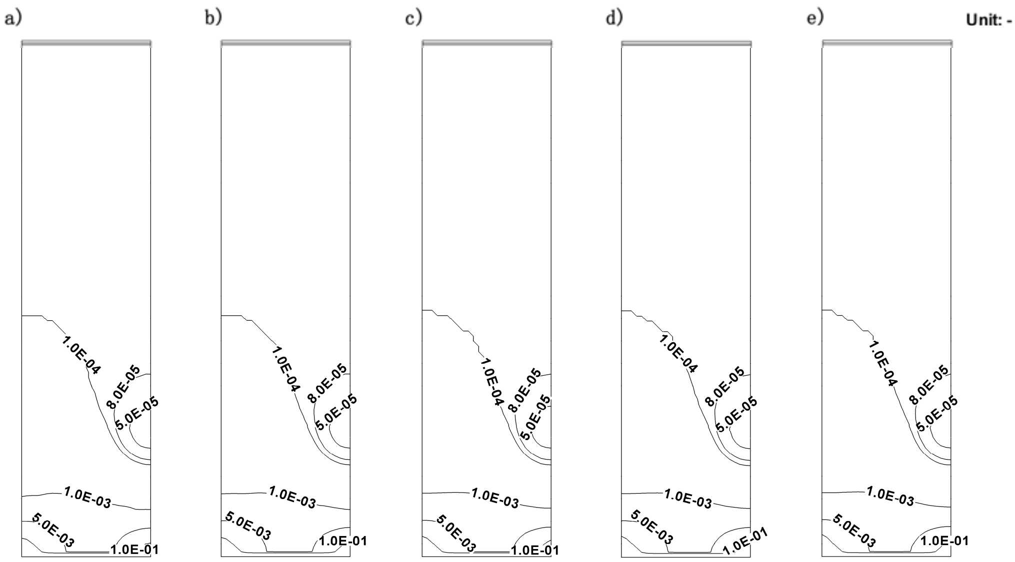

Figure 5. The effect of powder density on its static holdup inside the furnace: (a) 1,500 kg/m^3; (b) 2,000 kg/m^3; (c) 2,500 kg/m^3; (d) 3,000 kg/m^3; (e) 3,500 kg/m^3

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3.3 Influence of Powder Feed Rate on Its Distribution

In this section, with the powder feed rate through gas inlet varied from 0.1 to 0.9 kg/m^2·s with the interval of 0.2 kg/m^2·s, the powder dynamic and static holdup distributions were compared in Figures 6 and 7 respectively.

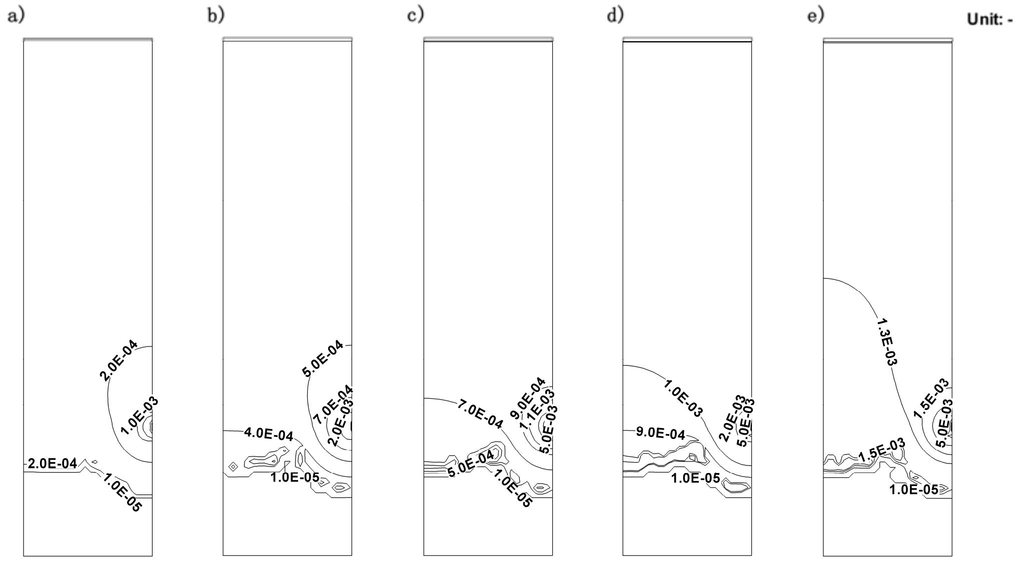

Figure 6. The effect of powder feed rate on its dynamic holdup inside the furnace: (a) 0.1 kg/m^2·s, (b) 0.3 kg/m^2·s, (c) 0.5 kg/m^2·s, (d) 0.7 kg/m^2·s, (e) 0.9 kg/m^2·s.

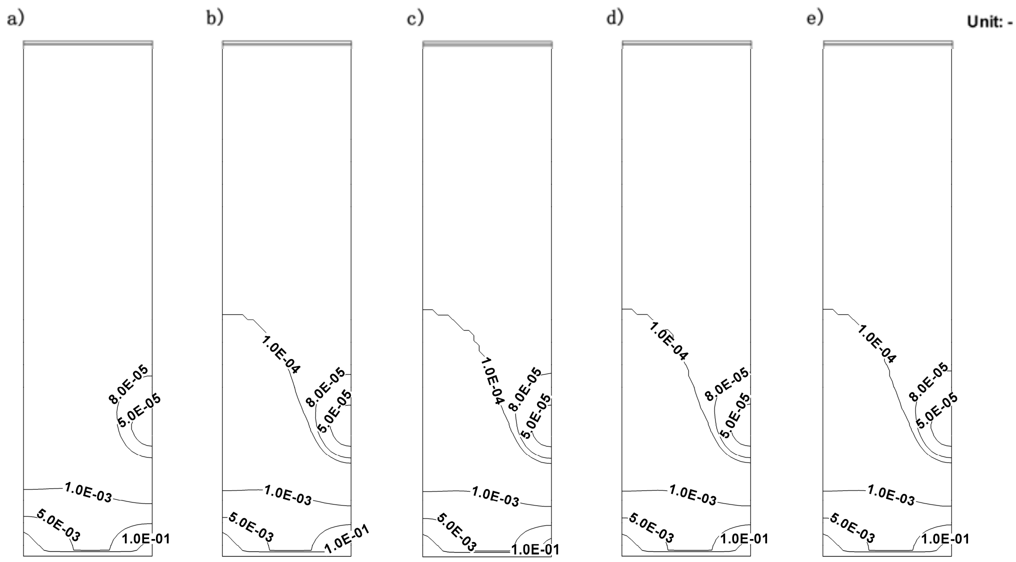

Figure 7. The effect of powder feed rate on its static holdup inside the furnace: (a) 0.1 kg/m^2·s, (b) 0.3 kg/m^2·s, (c) 0.5 kg/m^2·s, (d) 0.7 kg/m^2·s, (e) 0.9 kg/m^2·s.

Since more powders were injected through the gas inlet, the increasing powder feed rate apparently gave rise to the powder dynamic distribution as shown in Figure 6. Meanwhile, similar to the results obtained from the previous section, the powder feed rate also made a neglectable influence on the dynamic distribution near the bottom region and the static holdup distribution inside the furnace.

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3.4 Influence of Man-made Deadman on Powder Distribution

Inside the pre-reduction shaft furnace, there was a man-made deadman designed to help convey the direct reduced iron from centre to edge under its own gravity. So in this section, the influences of two kinds of man-made deadman shapes, one being 1 m in x direction and 4 m in y direction (1-4) and the other 2 m in both directions (2-2), on the inner powder dynamic and static distributions were compared with the results shown in Figure 8 and 9 respectively.

In the Figures, 1-4 man-made deadman directly changed the powder dynamic distribution near the symmetry because of its greater height in axial direction, and the central corner accumulated the motional powder with the holdup reaching to as great as 1.0e-3. However, since the 2-2 man-made deadman located in the zone with a relatively low gas velocity, the corner effect contributed little to the powder dynamic distribution. As for the powder static holdup distribution, the increasing length of man-made deadman in radical direction definitely helped to eliminate the blockade zone in the centre. As a whole, under the premise of ensuring smooth flow of solid particles inside the furnace, the man-made deadman should be designed wider and lower, therefore 2×2 man-made deadman was preferred in comparison with 1-4.

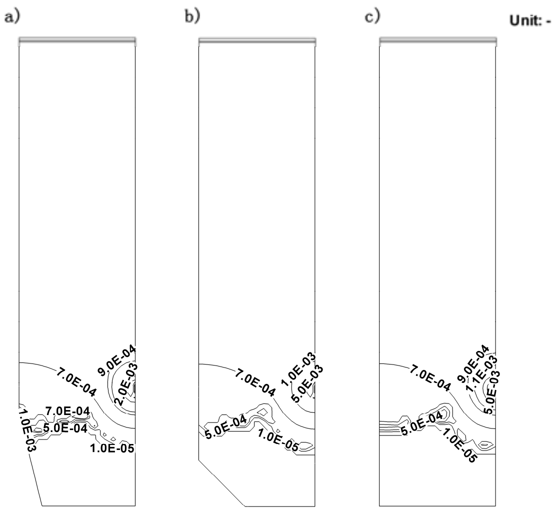

Figure 8. The effect of man-made deadman shape on its dynamic holdup inside furnace: (a) 1-4, (b) 2-2, (c) base case.

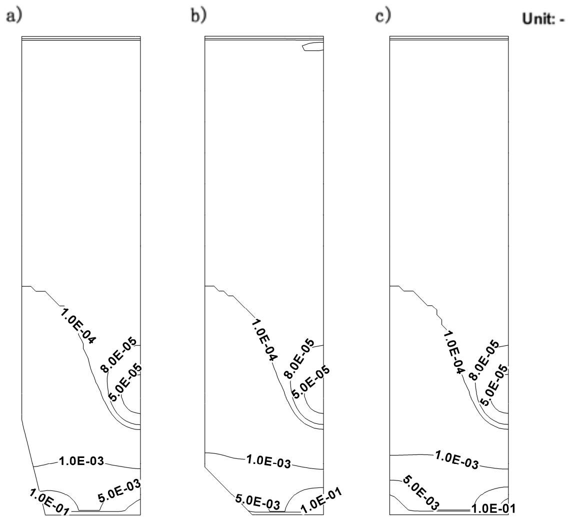

Figure 9. The effect of man-made deadman shape on its dynamic holdup inside furnace: (a) 1-4, (b) 2-2, (c) base case

3.5 Further Comparison and Discussion

Taking the inlet horizontal level (5 m above the bottom) as an example, both the dynamic and static holdup distributions along radical direction under above different factors (powder density, feed rate and man-made deadman shape) were collected and compared in Figure 10.

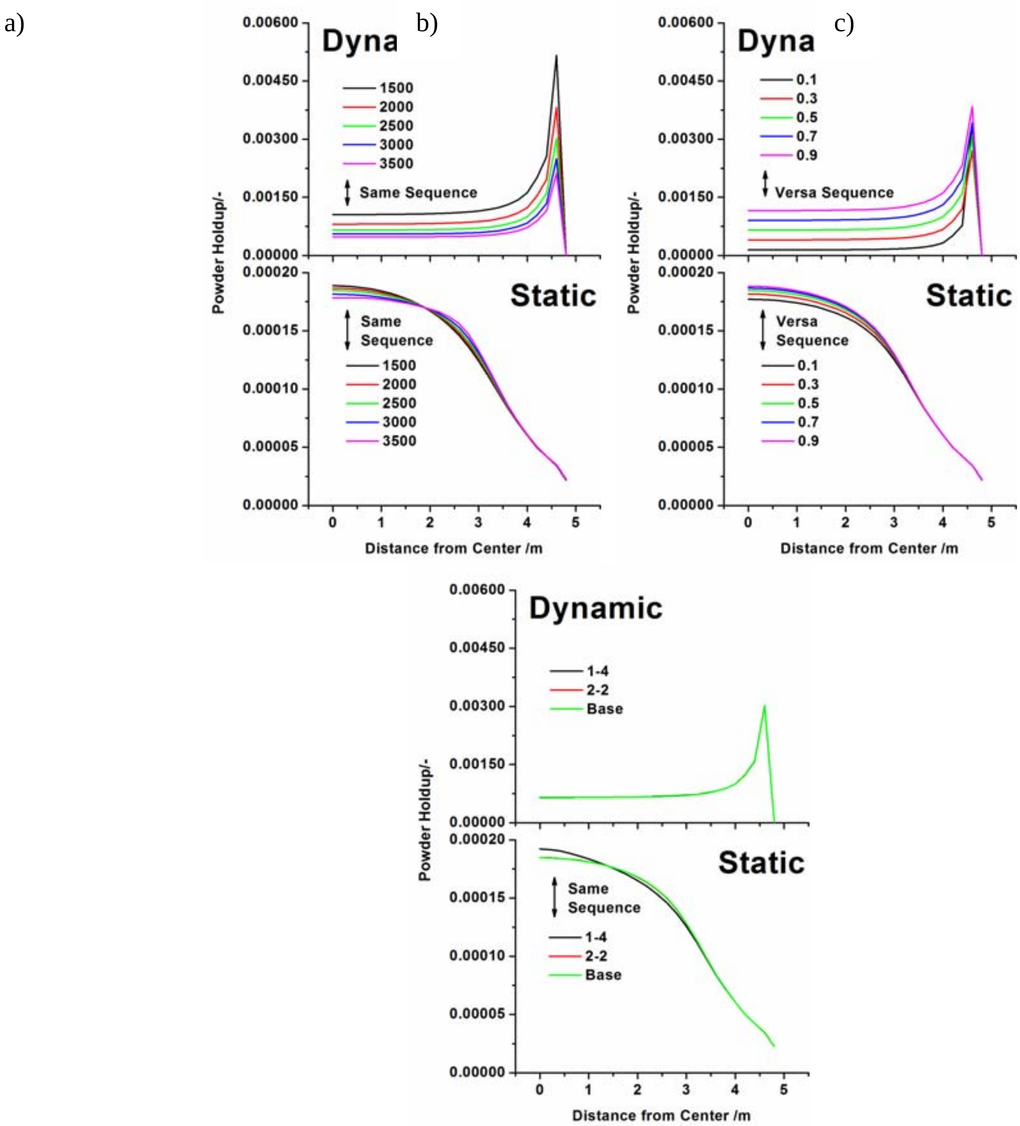

Figure 10. The comparison of both dynamic and static holdup distribution at inlet horizontal level (5 m height from bottom) under the variation on (a) powder density, (b) feed rate and (c) man-made deadman shape.

At the gas inlet level, from Figure 10a, it could be seen that as the gas contained more dust from the iron-bearing burden decomposition than that from coal or coke gasification, the increasing powder density not only decreased the peek dynamic holdup near the inlet from 5.2e-3 to 2.1e-3, but also decreased that near the centre from 1.1e-3 to 4.8e-4, but the powder dynamic holdup gradient with increasing density gradually decreased. On the other hand, the powder dynamic holdup also characterized with the same trend as the feed rate decreased as shown in Figure 10b, but its gradient kept almost constant. As for the powder static holdup under different cases and the powder dynamic holdup with varied man-made deadman shape, the

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corresponding values kept practically unchanged with a maximum difference less than 7.0e-5. In all, the powder mainly existed in the form of motion in the gas rather than staying on the surface of solid at the inlet horizontal level.

In addition, the authors also investigated the influences of other factors, such as the particle diameter of solid and powder, the packed bed voidage and the gas volume flow, on both powder dynamic and static holdup distribution behaviors. Due to the space constraints, only parts of the works were presented in this paper. From the above analysis, neither the powder density nor its feed rate affected the static holdup distribution, which was found to demonstrate a negative relationship with the two key factors, gas volume flow velocity and solid particle diameter. In another word, increasing the gas velocity or updating the packed bed with larger diameter particles would decrease the powder static holdup as well as narrow the existing static powder region.

4 CONCLUSIONS

In order to realize the sustainable development of iron and steel industry, cutting down CO_2 emission from iron and steel plants, especially in blast furnace ironmaking processes, has become a big concern around the world. In recent years, some non-blast furnace ironmaking processes are proposed and even put into production to meet the environmental requirement. The most important characteristic of those new processes is the introduction of pre-reduction shaft furnace. Instead of natural gas or oil, the reducing gas is mainly produced by coal combustion, so it would contains plenty of unburned fine or other powder, iron-bearing materials for example. The powder distribution behavior inside the furnace has direct and important influences on the packed bed permeability, thus causing the increase of pressure drop and the decrease of reduction efficiency. The present work studied the basic powder distribution in the form of dynamic and static holdup, and the influences of powder density, feed rate and man-made deadman shape on above behaviors were further investigated and compared. Under the present conditions, the results could be summarized as below.

- At the middle and upper part of the shaft furnace, the powder preferred to flow in the gas form rather than stay on the surface of solid. By contrast, due to the relatively low gas velocity in the inactive zone below the gas inlet, the powder formed two blockade zones in the centre and the wall region of the bottom respectively.
- As the gas ascended from the inlet to the furnace top, the dynamic holdup of powder firstly increased to 3.0e-3 as a result of the changed gas flow direction, and then decreased to 7.0e-4. However, the static holdup gradually increased with the increasing distance away from gas inlet to as high as 1.8e-4 near the centre.
- The increase of the powder density generally reduced the dynamic holdup inside the furnace except the region near the bottom, but the gradient with respect to the density decreased. On the other hand, the increase of the powder feed rate definitely gave rise to the dynamic holdup and such gradient almost remained constant.
- The higher height in axial direction of the man-made deadman formed a corner to accumulate the dynamic powder to about 1.0e-3, however its wider diameter in radical direction could eliminate the blockade at the central bottom

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of the furnace. As a result, the man-made deadman with a lower height and a larger diameter needed giving first priority.

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