Two Dimensional Cold Model Study on Unstable Solid Descending Motion and Control in Blast Furnace Operation with Low Reducing Agent Rate

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Unsteady behavior with bridging/slipping of solid bed in low reducing agents rate operation of blast furnace was simulated using a two dimensional cold model. Alumina sphere was used as representative particle of coke/ore packed bed. Two kinds of deadman particles different in gas permeability was examined. To simulate the effect of cohesive zone on unsteady behavior, a sand layer of lower gas-permeability was charged with a certain thickness at the top of the bed, which descended with a form of cohesive zone when it reached at the lower part. Further, a fine coke layer was set at the shaft bottom with a certain size assuming accumulation of fines. Unsteady phenomenon with the fine coke accumulation was observed with another thin sand layers, charged in the shaft assuming increase of gas-permeability resistance in lower reducing agents rate operation. It was revealed that the ratio of peripheral flow rate to the total gas injection rate had a considerable effect on the discontinuous behavior of both solid descending motion and gas static pressure. The ratio increased with decline in deadman gas-permeability, approach of the simulated cohesive zone to deadman surface and inflow of small particles into raceway. There was a lowest critical position of the simulated cohesive zone for the rapid increase of discontinuity. The bridging/slipping behavior with fines accumulation was significantly affected by the low gas-permeability layers charged in shaft. Setting up the chimney zone of high gas-permeability at the central part was effective to decrease the discontinuous motion.

KEY WORDS: blast furnace; low reducing agents; moving bed; solid flow; unstable solid behavior; bridging; slipping.

1. Introduction

Low reducing agents rate operation in blast furnace is on a focused attention to reduce the emission of CO₂ gas for the greenhouse effect. It is considered that the unstable behavior of burden material such as bridging and slipping would become severer by reducing the coke supply. The unstable motion would be caused on the following gas/solid dynamics or gas/solid reaction both in the lower part and in the shaft of blast furnace. In the lower part, the cohesive zone would shift downwards and be settled at a lower position for the low reducing agents rate operation compared with the normal operation. Unsteady phenomenon with the fine coke accumulation was observed with another thin sand layers, charged in the shaft assuming increase of gas-permeability resistance in lower reducing agents rate operation. It was revealed that the ratio of peripheral flow rate to the total gas injection rate had a considerable effect on the discontinuous behavior of both solid descending motion and gas static pressure. The ratio increased with decline in deadman gas-permeability, approach of the simulated cohesive zone to deadman surface and inflow of small particles into raceway. There was a lowest critical position of the simulated cohesive zone for the rapid increase of discontinuity. The bridging/slipping behavior with fines accumulation was significantly affected by the low gas-permeability layers charged in shaft. Setting up the chimney zone of high gas-permeability at the central part was effective to decrease the discontinuous motion.

The flame brightness observed from tuyere fluctuates in cycles.¹ The flame brightness observed from tuyere fluctuates in cycles.² Concerning this phenomenon, the cyclic inflow of coke or coke/ore mixture to raceway is suggested. The drag for gas to permeate such a narrow coke flow channel would become great if the gas flow rate is kept constant. Therefore, the gas charged from the tuyere is intended to flow up vertically and the peripheral gas flow become dominant, eventually to prevent smooth solid downward flow into the race way. Decrease of the coke slit width in the cohesive zone due to the low coke supply causes also increase of gas drag.

On the other hand, the volume ratio of the ore-coke mixing layer formed when coke and ore are charged alternately would become large under low coke supply. Accordingly, the total drag by gas permeation through the shaft would increase by both decrease of the width of coke layer with larger voidage and increase of the ratio of ore-coke mixing layer with smaller voidage. In this situation, gas may select wall-side flow channel because of the larger voidage, resulting in the wall-side slip when a large amount of gas generated in the lower part blows out at the top of the furnace.³ Moreover, lots of fine coke would be generated by mechanical destruction during descending because more porous coke with low strength increases since low reducing agents rate operation forces more load in chemical reaction against coke. Kojima et al.⁴ state on the dissection research of blast furnace that fine coke mainly distributes in the regions below the shaft middle and around the tuyeres. Tate et al.⁵ discuss also in their hot model experiment that the fine coke accumulation around the combustion zone would cause unstable furnace performance.

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On the background stated above, the purpose of this investigation is to simulate experimentally the unstable behavior of packed bed including bridging/slipping using a two-dimensional cold model of blast furnace. A technique with a solid particle bed of lower gas-permeability, initially charged as a horizontal layer and descends with a form as if it were cohesive zone when it reaches at the lower part of the model furnace, is adopted in order to evaluate the effect of the size of coke funnel-flow channel on the unstable bed motion. Further, setting initially a fine coke layer at the bottom of the shaft assuming accumulation of the fines, the experiment is carried out with a technique simulating the decline in gas-permeability in the upper part of the blast furnace. The relationship between fine-solid inflow to raceway and unstable packed-bed motion is also investigated on the view that the fine-solid inflow would decrease the gas permeability from raceway to surrounding packed bed. The measurement to detect the unstable bed motion is carried out while the solid material used for the above-mentioned purposes descends to reach the raceway and flows in it. The methods for controlling the instability of solid flow are also suggested.

2. Experiment

A two-dimensional, half model of blast furnace consisting of transparent, acrylic resin sheets, was used in the experiment. The schematic diagram is shown in Fig. 1. The consumption of coke in the raceway of blast furnace was simulated by discharging particles from a pipe of 38 mm inner diameter attached to the back surface with the angle 45°. The particles were also discharged at a low rate from a sub-pipe attached to the vertical wall in order to keep deadman height at constant level. The discharging rates of particles from both the raceway and sub-pipe were regulated respectively, using electromagnetic feeders installed in a closed box. A set of four pipes as a tuyere, 0.9 cm in each pipe inner diameter, is installed to the wall below the bottom of bosh. When tuyere depth into the bed = 0, raceway behavior becomes more unstable with a vertically expanded raceway accompanying with discontinuous particle discharge.6) We adopted this tuyere condition in this study, supposing that blast furnace operation proceeds under similar situation. The air was supplied at room temperature from the tuyere and was exhausted from the top of the bed. No air flowed downwards because the particle discharge was carried out in the closed box. A two-dimensional apparatus.

Table 1. Physical property of particles.

| Material | Alumina sphere | Sand A | Sand B | Sand (A+C) | Fine coke |
|----------|----------------|--------|--------|------------|-----------|
| \( d_2 \) (mm) | 2.6 | 1.9 | 1.2 | 0.6 | 0.55 |
| \( \rho_0 \) (kg/m³) | 2600 | 2590 | 2615 | — | — |
| \( \rho_h \) (kg/m³) | 870 | 1350 | 1345 | 1455 | 671 |
| \( e \) (—) | 0.42 | 0.48 | 0.48 | 0.44 | 0.45 |
| \( u_{w} \) (m/s) | 1.02 | 0.976 | 0.732 | 0.335 | 0.224 |
| \( \varphi \) (°) | 1 | 0.6 | 0.7 | 0.9 | 0.8 |
| \( \theta \) (°) | 29 | 41 | 37 | 37 | 40 |
| \( f_{w} \) (Ns/m²) | 1822 | 5102 | 9398 | 34240 | 25360 |
| \( f_{w} \) (Ns/m²) | 6344 | 8690 | 11790 | 25650 | 17690 |

*Estimated value, **Calculated value, ***\( \langle P/L,f_{w}(U+f_{w}U) \)
er, any similarity on fluid drag between the model and practical furnace was not taken into consideration.

The case for the deadman consisting of sand A of lower gas-permeability, instead of alumina particles, was also examined supposing that in low reducing agents rate operation of blast furnace, the gas permeability through deadman would decrease because of smaller coke diameter and fine coke accumulation on the deadman surface. Deadman of sand A was arranged in shape artificially to have the same shape as in alumina particle.

Further, the experiment with an imperfect horizontal sand layer having “a non-sand packing region” in the section of 5 or 10 cm from the vertical wall of the equipment was also carried out. The region was filled by alumina particles instead of sand A. Since alumina layer has a higher gas-permeability than the sand layer, gas may be easy to flow up through this region. In other words, we expected a chimney effect for gas flow channel in this technique.

In all the experiment, the displacement of descending solid surface at peripheral position, gas static pressure 40 mm upside the center of the discharging pipe (B1) and solid compressive stress at the belly-top wall were measured.

- **Experiment 2**: Solid bed behavior with a ‘fine coke layer’ packed initially at the shaft bottom assuming local accumulation of fine coke, was studied in such a way as to simulate the decline in shaft gas-permeability in the low reducing agents rate operation as stated below. The initial setting of fine coke at the shaft bottom is innovated referring to the report by Kojima et al.4) The thickness of the fine coke layer is chosen 5 or 15 mm, and the width measured from the shaft wall is 40, 80, 160 mm and full span to the vertical wall. Three layers of sand B, 5 mm in each thickness, were packed like sandwich with the distance 5 cm between layers in the upper part of the shaft as ‘a zone of low gas-permeability.’ In settling such an experimental technique, however, the similarity concerning the drag of gas is not considered the same as in Experiment 1. The displacement of the top surface and gas static pressure at the belly to shaft wall were measured.

Three kinds of gas velocity were chosen from the same consideration as the previous paper,8) based on the transportation of fine coke particle passing through the void space of coarse particle bed. A regular cubic arrangement of equal spheres was assumed for the packing structure of the coarse alumina particle bed, standing on that the void fraction is close to the regular cubic arrangement ($\varepsilon = 0.476$). Defining $F_D$ as the fluid drag and $F_E$ as the external force exerted by a single fine particle, if $F_D$ is greater than $F_E$, then the fine can fall down overcoming the drag force. The gas velocity was determined considering the force balance on a single particle in the minimum constriction part of the model packing structure, as follows: $U_B = 35 \text{ m/s}$ for the condition $F_D > F_E$, and $U_B = 28 \text{ m/s}$ for $F_D < F_E$ at the bottom level of the shaft. $U_B = 31 \text{ m/s}$ is the intermediate value. In general, the condition $F_D > F_E$ would enable the transportation of the fine coke particles through the void space (say, flooding of fines). On the other hand, in the condition $F_D < F_E$, fine particles would descend together with coarse.

The experimental conditions are shown in Table 2 for both Experiment 1 and 2. The coefficients, $f_1$ and $f_2$, representing measure of fluid drag calculated based on Ergun’s equation, are also listed in Table 1, where $U$ is superficial gas velocity.

3. Experimental Results and Discussion

### 3.1. Experiment 1

It was found from the change of displacement of the top surface during discharging that the particles moved downward repeating stoppage of motion and slipping. This discontinuous movement corresponded completely to the raceway behavior with expansion and contraction in size. The top surface kept stationary state during expanding and fell down together with contraction, i.e., collapse of the bridging of raceway material. The experimental data obtained by Experiment 1 is listed in Table 3.

### 3.1.1. Behavior without Horizontal Sand Layer

(1) **Effect of Gas Flow**

Run 1-1 in Table 3 is the result for no gas supply, $U_B=0$, it represents a basic motion of alumina particles under

| Table 2. Experimental condition. |
|----------------------------------|
| | Experiment 1 | Experiment 2 |
| | (a) | (b) | (c) |
| $u_s$ (m/min) | 0.019 | 0.019 | 0.019 |
| $U_B$ (m/s) | 40 | 28 | 31 |
| $u_i$ (m/s) | 0.55 | 0.39 | 0.43 |
| $W_B$ (kg/min) | 0.22 |
| $W_C$ (kg/min) | 0.02 |

$u_s$: superficial velocity at the bottom level of the shaft

| Table 3. Result of Experiment 1. |
|----------------------------------|
| | Material of horizontal layer | Deadman material | Time (min) | Bridging/slipping frequency (g) | Slipping distance (mm) |
| | (Horizontal charge) | | | | |
| 1-1 | Non $U_B=0$ | Alumina** | 0-12 | 0-0.2 | 0.05-0.2 |
| 1-2 | Non | Alumina | 0-12 | 1.5-2.5 | 0.5-1 |
| 1-3 | Sand A | Non | 0-12 | 8-15 | 5-7 |
| | (Horizontal charge) | | | | |
| 1-4 | Sand A | Alumina | 10-10.5 | 1.5-3 | 0.5-2 |
| 1-5 | Sand B | Alumina | 10.5-12 | 2.5-12 | 3.5-5 |
| 1-6 | Sand A | Alumina | 10-9 | 1.5-12 | 4.5-6 |
| 1-7 | Sand A | Alumina | 11-15 | 20-23 | 9-11 |
| 1-8 | Sand B | Alumina | 11-15 | 20-23 | 9-11 |
| | (Horizontal charge) | | | | |
| 1-9 | Mixture layer | Sand A | 0-5 | 5-9 | 3-6 |
| | (20-30 cm) | | 5-6 | 10-17 | 7-12 |
| 1-10 | Sand A, Chimney | Sand A | 0-6 | 5-9 | 3-6 |
| (width, 10 cm) | | | 6-12 | 12-17 | 6-9 |
| 1-11 | Sand A, Chimney | Sand A | 0-7 | 5-9 | 3-6 |
| (width, 5 cm) | | | 7-12 | 15-19 | 7-12 |
| 1-12 | Sand B, Chimney | Sand A | 0-6.5 | 4-8 | 1.5-3 |
| (width, 10 cm) | | | 6.5-8 | 9-18 | 4.5-8 |
| | | | 8-12 | 18-24 | 9-13 |

*gas inject velocity $U_B=40 \text{m/s}$ except for Run 1-1

**Alumina sphere

***charged position : distance from top of the equipment
Gravity only, showing a successive small discontinuous slipping and stoppage motion with a short frequency. Run 1-2 shows that the effect of gas flow on the solid motion is clear with a larger discontinuity at $U_B = 40 \text{ m/s}$.

(2) Effect of Deadman Permeability

Although the blast velocity $U_B$ was set the same in every operation as $U_B = 40 \text{ m/s}$, the local velocity, especially, in the lower part of the equipment depended on each experimental condition, therefore, the solid behavior varied as stated below.

Material composing of deadman is alumina particle in Run 1-2 and sand A in Run 1-3. The change with time of bridging/slipping frequency at the top of the bed, gas static pressure and wall normal solid stress are shown in Fig. 2. The flat part in laser displacement means the period with no particle motion when the bridging occurs, and the sudden increase means the descent by slipping. A sudden change in the solid stress with a set of decrease and increase at a moment of slipping and bridging, respectively is clearly shown in Fig. 2(b) in the case of sand deadman. This phenomenon probably corresponds, respectively, to loosening of packing state at flowing into raceway and such a passive state of stress that could sustain solid load acting on arch.

The gas static pressure increased during bridging accompanying with expansion of raceway and then suddenly dropped in slipping in the case Fig. 2(a) or attained a maximum value before the drop in slipping as shown in the case Fig. 2(b). Figure 3 shows an example of the variation of static pressure corresponding to the size of raceway obtained in Run 1-3 (i.e., the case Fig. 2(b)). The pattern of variation of the static pressure changed depending simply on whether the raceway of large void space expanded vertically beyond the pressure tap position or not. The static pressure becomes lower in the raceway due to the high revolution of gas.

The bridging/slipping frequency and slipping distance increases significantly in Run 1-3 with sand A deadman as shown in Fig. 2. The frequency and the distance was about 5 to 6 and 7 to 10 times, respectively, as large as Run 1-2. The reason why the discontinuity of solid flow increased is attributed to that it is easier for injected raceway gas to flow up vertically with high velocity rather than it penetrates through the sand deadman of lower gas permeability and this makes the fluid drag against a particle block being on the raceway increase so as to be able to sustain the solid load. The static pressure measured at B1 was considerably high in Run 1-3 compared with Run 1-2 as shown in Fig. 2 although the injected gas rate was the same. This means the peripheral flow was prevailing in Run 1-3 with sand A deadman.

3.1.2. Behavior with Horizontal Sand Layer

(1) Case of Alumina Deadman

The change of the horizontally charged sand layer with time in Run 1-4 is shown in Fig. 4. Comparing Run 1-4 with Run 1-2, let us discuss the effect of the sand layer on solid behavior. Figure 5 shows the bridging/slipping frequency and slipping distance during time 540 to 720 s. The discontinuity in Run 1-4 is nearly equal to that in Run 1-2 until 10.5 min (630 s) after the start of operation, however, after the 10.5 min the discontinuity in Run 1-4 becomes remarkable. The simulated cohesive zone (i.e., sand layer) was approaching deadman during this period as supposed from the flow pattern of Fig. 4.

The large discontinuity may be caused on the following mechanisms. When the same gas flow rate is intended of keeping, strong drag acts on the sand layer due to the low permeability in such a way as to sustain the solid load from upper area. This contributes, further, decreasing of solid load on the raceway that makes the particle inflow into...
raceway difficult under the gas drag.

The appreciable approach of the simulated cohesive zone to deadman surface could also be a cause for the discontinuity. When a large part of the funnel flow channel is occupied by the quasi-stagnant region, developing on deadman and as if particle motion is stationary,\textsuperscript{6, 7, 9} the flowing channel of a larger void fraction is significantly reduced, in other words, the smooth inflow of particles into the raceway is prevented. Gas vertical flow would also strengthen to halt the solid descent and to cause the successive sudden inflow of the ‘simulated cohesive zone’ into the raceway.

Adding to the mechanisms mentioned above, the discontinuity could be developed significantly by inflow of small particle of the sand layer into the raceway. Actually, the inflow formed initially a thin sand layer of lower gas-permeability at the boundary between raceway and deadman along bottom of raceway to the raceway back as seen later. The vertical, peripheral flow of gas could be developed by this phenomenon. Comparison of Run 1-5 using sand B layer with Run 1-4 also shows the same result as mentioned above, although the discontinuity became somewhat larger than in Run 1-5 because the gas permeability of sand B is lower than that of sand A. Tate \textit{et al.} \textsuperscript{5) using a hot model with the mixture of coarse and fine cokes, observed fine coke accumulation layer around the combustion zone expanding upwards. The present result could support their assumption that such a situation of combustion zone might be related to the unstable behavior observed in the test blast furnace.

(2) Case of Sand Deadman

Let us compare Run 1-6 with Run 1-3. Figure 6 shows the flow pattern and discontinuity in Run 1-6. From Table 3, it is clear the degree of discontinuity in Run 1-6 is nearly equal to Run 1-3 until 9 min (540 s in Fig. 6) after the start of the operation. The discontinuity became large gradually after that time and significant discontinuity appeared by the same causes as stated in the case (1). After 12 min, the raceway material was replaced completely by sand with very serious discontinuity.

The discontinuity in Run 1-6 was larger than in Run 1-4 because the gas permeability of deadman material was lower. Run 1-8 with sand B layer with smaller in particle diameter, showed large discontinuity, especially after when the raceway material was replaced by sand B. The behavior of raceway in this situation is shown in Fig. 7. The sand was fluidized in a slugging state, which is similar to the behavior assumed by Tate \textit{et al.} based on the hot model result.\textsuperscript{5)}
The charging of sand mixture layer having the volume ratio of sand A to sand C equal to 7 : 3 was intended to make the gas permeability of sand layer lower. The result is given with Run 1-9. When the mixture layer was in the upper part of shaft, there was no remarkable difference in discontinuous behavior compared with the cases of single sand layer. However, when the sand C began to flow into the raceway and the thin layer of sand C was formed at the boundary between raceway and deadman, such a considerable discontinuity with bridging time 90 s and slipping distance over 50 mm was found that could not be observed in the case of single sand A or sand B layer. The expansion of raceway corresponding to the change of solid motion and static pressure with time is shown in Fig. 8. The whitish material is sand C in the figure. As a result, accumulation of small particle layer at the edge of the raceway is an important factor for discontinuous solid motion.

(4) Chimney Effect

The results are shown in Table 3 with Run 1-10 to 1-12. Figure 9 shows the flow pattern and discontinuous behavior comparing Run 1-10 with Run 1-7. It is obvious from Fig. 9 that the discontinuity is reduced by a chimney effect. More smooth flow was established by keeping with higher gas-permeability near the center vertical wall. Gas flow was changed from peripheral to central flow bringing about the decrease of the static pressure. The effect of chimney size was not remarkable (Run 1-10 and Run 1-11).

(5) The Span of Funnel Flow Channel and Discontinuity

(3) Horizontal Layer of Sand Mixture (A+C)

The charging of sand mixture layer having the volume ratio of sand A to sand C equal to 7 : 3 was intended to make the gas permeability of sand layer lower. The result is given with Run 1-9. When the mixture layer was in the upper part of shaft, there was no remarkable difference in discontinuous behavior compared with the cases of single sand layer. However, when the sand C began to flow into the raceway and the thin layer of sand C was formed at the boundary between raceway and deadman, such a considerable discontinuity with bridging time 90 s and slipping distance over 50 mm was found that could not be observed in the case of single sand A or sand B layer. The expansion of raceway corresponding to the change of solid motion and static pressure with time is shown in Fig. 8. The whitish material is sand C in the figure. As a result, accumulation of small particle layer at the edge of the raceway is an important factor for discontinuous solid motion.

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(5) The Span of Funnel Flow Channel and Discontinuity

The effect of the span of funnel flow channel between the simulated cohesive zone and deadman surface on the discontinuous behavior, discussed before, is summarized in

Fig. 8. Correspondence between raceway size and discontinuity (Run 1-9).

Fig. 9. Chimney effect with sand B layer.

Fig. 10. Effect of distance between raceway and sand layer on bridging/slipping frequency.

Fig. 11. A model representing force balance on particle bed.
ing collapsing height $H$ and width $S$ equal to raceway depth. Putting the average shear force acting sides the block $T$, gravity $G$ and fluid drag $F_f$, the relation holds $F_f + T > G$ in arching state. A critical condition for collapsing of arch may be given by the force balance $F_f = G$ putting $T = 0$, then considering the relation $\Delta P(SL) = (SLH)\rho_t g$, the following equation holds.

$$\Delta P/H = \rho_t g.$$

(1)

$\Delta P$ is pressure drop for the height $H$. When gas permeates the block with average superficial velocity $U_g$, the following relation is derived from Ergun’s equation assuming the turbulent term is only effective.

$$\frac{\Delta P}{H} = \frac{U_g^2}{\lambda}; \lambda = \frac{1}{4} \left( \frac{1.75(1-e)\rho_t}{\varrho} \right)$$

(2)

Volumetric flow rate of gas flowing vertically through the block is given by $Q_v = SLU_g$, accordingly the relation holds.

$$Q_v = \frac{\sqrt{\lambda \Delta P/H}}{\varrho}$$

(3)

The representative pressure drop was evaluated from the difference between the injecting gas pressure and the static pressure measured at the position B1 in Fig. 1, and the value of collapsing height $H$ was determined from the video images. The index of peripheral flow $\eta$ was defined as follows.

$$\eta = \frac{Q_v}{Q_t}$$

(4)

$Q_t$ is the total gas injecting rate from the tuyere. The estimated index of peripheral flow $\eta$ is shown in Fig. 12. In the case of alumina particle only without sand layer, $\eta$ was nearly 0.5. On the other hand, Fig. 12 shows that in the case with sand layer the peripheral flow develops as the sand layer approaches deadman surface, and the maximum value is attained when the sand began to flow into the raceway. The successive decrease in $\eta$ when the raceway is replaced by sand means the model is not effective any more in such a condition. It was confirmed also from a simple model that the discontinuous bridging/slipping behavior had deep relation with the peripheral flow of gas out of the raceway.

3.2. Experiment 2

The obtained experimental results are summarized in Table 4. The behavior of fine coke is described with the terms ‘crack, flooding, bridging and bridging/collapsing’. The crack behavior is defined as that the crack space is formed just under the fine coke layer but the fine layer can also descend with collapsing/reformation of crack. Flooding is defined as the fine coke particles are transported upwards by gas through the void space to diffuse or spread out into the bed. The flooding can also occur together with fines descending motion. The term ‘descent’ is used for the behavior with descending motion.

3.2.1. Effect of Gas Flow

As seen clearly in Table 4, the crack or bridging/collapsing developed in general at the higher velocity $U_b = 35 \text{ m/s}$, independent of the existence of low gas-permeability material in the upper part of equipment or the difference of

| Run No. | Thickness w (mm) | Width f (mm) | Gas velocity $U_b$ (m/s) | Deadman material | Sand B in shaft* | Fines behavior |
|---------|------------------|--------------|----------------------|------------------|-----------------|---------------|
| 2-1     | 5                | 80           | 35                   | Alumina          | non             | crack-s***/flooding |
| 2-2     | 15               | 80           | 35                   | Alumina          | non             | crack-s/descent/flooding |
| 2-3     | 15               | 160          | 35                   | Alumina          | non             | crack/descent/flooding |
| 2-4     | 15               | full span   | 35                   | Alumina          | non             | bridging |
| 2-5***  | 15 (full span)/2 | 35           | Alumina              | non             | crack-s/descent/flooding |
| 2-6     | 5                | 80           | 28                   | Alumina          | non             | descent/flooding |
| 2-7     | 5                | 160          | 28                   | Alumina          | non             | crack/descent |
| 2-8     | 5                | 80           | 31                   | Alumina          | non             | descent/flooding |
| 2-9     | 5                | 160          | 31                   | Alumina          | non             | descent/flooding |
| 2-10    | 5                | full span   | 35                   | Alumina          | non             | flooding |
| 2-11    | 15               | 160          | 35                   | Alumina          | yes            | bridging/slipping |
| 2-12    | 15               | 80           | 35                   | Sand A           | non             | bridging/slipping |
| 2-13    | 15               | 80           | 31                   | Sand A           | non             | descent/flooding |
| 2-14    | 15               | 80           | 31                   | Sand A           | yes            | descent/flooding |
| 2-15    | 5                | 80           | 35                   | Sand A           | non             | flooding |
| 2-16    | 5                | 80           | 31                   | Sand A           | non             | descent/flooding |
| 2-17    | 15               | 40           | 35                   | Sand A           | non             | crack/s-collapsing |
| 2-18    | 15               | 40           | 35                   | Sand A           | yes            | crack/descent/flooding |
| 2-19    | 15               | 160          | 35                   | Alumina          | yes, with chimney | crack /flooding |

*Three layers of sand B with each thickness of 5 mm
**Small crack
***Fines layer was set at the position, (shaft height/4) on the belly top

Fig. 12. Change of peripheral flow index with time.
deadman material and the flooding took place as time proceeded. At the velocity \( U_1 = 31 \) and \( 28 \text{ m/s}, \) the bridging did not appear but descending motion with flooding became representatively. \( U_1 = 35 \text{ m/s} \) is a velocity for single fine coke particle to be transported through the void space as stated in the Sec. 2. The bridging comes out when lots of fines gather at the same time around the void space to block the channel. It can be concluded that there exist ‘a critical minimum gas velocity’ over which the crack or bridging can develop.

3.2.2. Effect of Thickness \( l \) of Coke Layer

The cases for the layer width \( w = 80 \text{ mm} \) and full span at \( U_1 = 35 \text{ m/s} \) are discussed here comparing Run 2-12 with Run 2-15 (deadman material: sand A) and Run 2-4 with Run 2-10 (deadman material: alumina particle) in Table 4. It is obvious that the crack or bridging/slipping enable to occur when the thickness \( l \) is large and the coke motion is occupied with flooding only for smaller thickness as \( l = 5 \text{ mm} \). This suggests there exist a critical minimum thickness for the accumulated fine coke layer to cause a crack or bridging/slipping.

3.2.3. Effect of Layer Width \( w \) of Coke Layer

**Figure 13** (Runs 2-2, 2-3 and 2-4 with alumina particle deadman) is shown to discuss the effect of accumulated layer’s width \( w \) on the discontinuous behavior. The crack or bridging developed easily with the wider width. The direction of gas up-flow is to be changed into the vertical wall side due to existence of the fine coke layer with lower permeability. This contraction of gas flow channel would bring a high pressure-loss when the same injection flow rate as in without contraction was intended. Accordingly, the static pressure just below the fines layer and therefore, the fluid drag would increase to cause a crack or bridging. A crack size with maximum 8 mm in height was observed in Run 2-3. If fine coke layer could be accumulated with full span as shown in Run 2-4, a more serious fluid drag would develop than the case of channel contraction and would sustain solid load acting on the fine coke layer for bridging. However, even if the full span accumulation is possible, the fines spread out and diffuse upwards when the thickness is small, as described in the Sec. 3.2.2. In this sense, a critical drag force enabling the crack or bridging must be evaluated as a function of accumulated layer’s thickness, the physical properties and gas velocity.

3.2.4. Effect of Low Permeability Sand B Layer in Upper Part of Shaft

Let us compare Run 2-3 with Run 2-11 having three layers of low permeability sand. The flow pattern in Run 2-11 is shown in **Fig. 14**. In Run 2-3 in Fig. 13, the fines descended forming a crack with the diffusion in gas flow direction. On the other hand, charging three layers of low permeability sand B in the shaft caused a big bridging under the coke layer as seen in Fig. 14. The reason can be attributed to that the low permeability layers yielded a large drag as to be able to sustain the solid load in the upper part, contributing decreasing of the solid load acting on the fine coke layer. **Figure 15** shows the change with time of static pressure and laser displacement in Run 2-3 (Fig. 13) in the case of no sand B layer. The initial static pressure dropped rapidly as the packing state changed from in a packed state into a
state of higher void fraction including crack space and then after the fines moved below the pressure decreased gradually together with the descent of the top surface. Although the change of laser displacement appeared as if it were linear, the detailed change corresponded to the formation of crack and slipping as shown in Fig. 16. The stepwise changes of the displacement are recorded in the figure, which means the coke layer descended with crack/slipping during a certain period. The crack shown in Fig. 13 occurs during the time about 11.5 to 15 s from the start of the operation in Fig. 16. Now, back to Fig. 15, serious bridging with increase in static pressure and slipping with sudden decrease in static pressure was observed during time 180 to 360 s. The slippage with distance 60 mm happened after long bridging period of 120 s at the top of the equipment. This behavior was caused by inflow of the fine coke into the raceway and forming thin layer of low permeability fines at the raceway boundary, this mechanism was already discussed in the Sec. 3.1 (Experiment 1). After the time 360 s, any discontinuity was not observed because the fine coke particle was discharged out and the thin layer disappeared. The change of static pressure and laser displacement with time in Run 2-11 (Fig. 14) is shown in Fig. 17. The figure consists of three stages of solid behavior. The first stage from 0 to 184 s is for the long term bridging showing a large pressure drop from the belly top to the shaft bottom and the slipping distance of about 70 mm is observed. The second stage is for the inflow of the fine coke into the raceway showing growth of the discontinuity as the inflow amount increases. The final stage is for the inflow of sand B layers into the raceway which have approached the lower part of equipment, showing smaller discontinuity than in the case of fine coke inflow. It is obvious the effect of the inflow on the discontinuity depends the particle diameter of inflow material, the smaller in diameter, the larger the discontinuity.

The effect of the low permeability sand B layer was considerable because the crack was also formed even if the fine coke layer was charged with small width as \( w = 40 \text{ mm} \). The flow pattern is shown in Fig. 18 that a crack about 4 mm in height is formed, and the successive crack/slipping motion was observed during first 180 s, and then inflow of fine coke and sand B occurred successively with the same large discontinuity as shown in Fig. 17.

Chimney effect was also examined with imperfect three layers of sand B, without packing sand B in the section 10 cm from the vertical wall. The operation, Run 2-19, was carried out by the same experimental condition as Run 2-11 (Fig. 14) and the result is given in Table 4. There was no occurrence of bridging. The chimney effect is again confirmed.

3.2.5. Effect of Permeability of Deadman Material

Finally, let us discuss the effect of permeability of deadman material on the discontinuity in the case without lower permeability sand layer in the upper part, comparing Run 2-2 with Run 2-12 in Table 4. In Run 2-2 with alumina particle deadman, the fine coke layer descended only with small crack/slipping and flooding. The flow pattern in Run 2-12 with sand A deadman and the change with time of static pressure and laser displacement are shown in Figs. 19 and 20, respectively. A clear bridging develops and the top surface slippage of about 10 mm in height at time 45 s is demonstrated in Fig. 20. After 45 s, the discontinuity decreases due to the loss of fine coke by the diffusion. It is demonstrated again that the peripheral gas flow advanced by lower gas-permeability of deadman affects significantly the discontinuous solid behavior.

4. Conclusion

The experimental investigation was carried out on the factors governing the unstable solid motion with bridging/slipping in low reducing agents rate operation of
blast furnace. Simulation for the cohesive zone of low gas-permeability with a sand layer revealed that the ratio of peripheral flow rate to the total gas injection rate had a considerable effect on the discontinuous behavior of solid motion and gas static pressure. The ratio increased with decline in deadman gas-permeability, approach of the simulated cohesive zone to deadman surface and inflow of small particles into raceway. There was a lowest critical position of the simulated cohesive zone, below which the discontinuity increased rapidly. It was considered that this condition would appear when cohesive zone shifted downwards to approach just the quasi-stagnant zone. The fine coke layer accumulated at the shaft bottom level also caused the discontinuous behavior being varied with the peripheral flow ratio. An existence of a critical fluid drag for bridging, as a function of gas velocity, thickness and width of accumulated layer and physical properties of the fines, was suggested. The motion of the fine coke layer was significantly affected by charging low gas-permeability layers in the shaft to bring about bridging. Setting up the chimney zone of high gas-permeability at the central part was effective to decrease the discontinuous motion in all the cases examined.

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Nomenclature
\[ d_p \]: Particle diameter (mm)
\[ f_1 \]: Coefficient of Ergun’s equation defined in Table 1 (Ns/m^4)
\[ f_2 \]: Coefficient of Ergun’s equation defined in Table 1 (Ns^2/m^5)
\[ F_D \]: Fluid drag on a single particle (N)
\[ F_E \]: External force exerted by a single particle (N)
\[ F_f \]: Fluid drag on a particle bed (N)
\[ g \]: Gravitational acceleration (m/s^2)
\[ G \]: Gravity (N)
\[ H \]: Collapsing height or thickness of bridge (m)
\[ L \]: Distance between front and back surfaces of apparatus (m)
\[ P \]: Static pressure of gas (Pa)
\[ Q_T \]: Total gas injection rate (m^3/s)
\[ Q_V \]: Peripheral flow rate (m^3/s)
\[ S \]: Raceway depth (m)
\[ T \]: Shear force (N)
\[ u_f \]: Superficial velocity at shaft bottom level (m/s)
\[ u_m \]: Minimum fluidizing velocity (m/s)
\[ u_s \]: Solid descending velocity at top of apparatus (m/min)
\[ U_B \]: Blast velocity (m/s)
\[ U_a \]: Average superficial velocity through bridging block of bed (m/s)
\[ W_R \]: Solid discharging rate (kg/min)
\[ W_S \]: Sub-discharging rate (kg/min)
\[ \varepsilon \]: Void fraction of particle bed (−)
\[ \eta \]: Index of peripheral flow (−)
\[ \theta \]: Angle of repose of particles (deg)
\[ \lambda \]: Value defined by Eq. (2)
\[ \rho_b \]: Bulk density of particle bed (kg/m^3)
\[ \rho_d \]: Density of gas (kg/m^3)
\[ \rho_p \]: Density of particle (kg/m^3)
\[ \varphi \]: Sphericity, defined by dividing the surface area of a sphere of the same volume as the particle by the surface area of the particle, \( \varphi = 1 \) for sphere (−)

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