Solid Behavior in Shaft and Deadman in a Cold Model of Blast Furnace with Floating–Sinking Motion of Hearth Packed Bed Studied by Experimental and Numerical DEM Analyses

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One of recent discussions is on the floating and sinking motion of packed bed in the hearth part of blast furnace while the molten liquid is stored in and tapped out of the hearth. Such a repetition motion might be profoundly related to the renewal of deadman particles. Thus, further analysis for deadman motion with the iron liquid is necessary to develop a method for controlled or stable furnace operation. In this study, the experiment is performed using a two-dimensional cold model with foaming polymer particles and water. Gas flow is not considered. The particle descending velocity in the shaft of the model is found to decrease with floating of the hearth packed bed and increase with the sinking motion. The deadman renewal rate that is the solid moving rate forced into raceway from the inside of deadman, is estimated by subtracting the descending rate from the total particle discharge rate being controlled at a constant rate. The numerical treatment called Discrete Element Method is also carried out to clarify the renewal mechanism with storing/tapping liquid. It is confirmed from both the experimental and numerical that the deadman particles move gradually into the raceway while storing/tapping liquid is repeated and the renewal of particles occurs in such a way that the older particles are forced to go out of deadman by buoyancy and the new particles come in to fill deadman through near the top of the deadman during tapping the liquid. The simulation indicates also that the wall normal contact force in the hearth part increases considerably when the particle bed floats.

KEY WORDS: blast furnace; two-dimensional model; storing/tapping liquid; deadman; renewal mechanism; renewal rate; DEM simulation; wall contact force.

1. Introduction

A large motionless or quasi-stagnant core region of coke called “deadman” is formed in the lower part of iron making blast furnace. This region is now recognized to play a significant role in total performance for blast furnace as to making a steady permeability for gas flow or a regular dropping path for molten liquid. It is reported that the deadman coke is replaced by new coke coming in through around the top of deadman. In our previous experiment by a semi-cylindrical cold model with water and particles of polymer foam under air injection, older particles in deadman were renewed while the hearth packed bed repeats floating by water storage and sinking by drainage. This renewal was caused by a driving force generated from the difference between liquid buoyancy and solid load due to gravitational force. The floatability of hearth packed bed for actual furnace was also examined theoretically and experimentally in the previous study. The further analysis for coke behavior in deadman with the molten liquid is required for developing a method for controlled or stable furnace operation.

The aim of the present paper is to clarify the deadman renewal mechanism and to evaluate the renewal rate that is the rate of solid movement forced into raceway from deadman while the hearth packed bed floats by buoyancy, based on both experimental and numerical methods. Deadman renewal due to coke consumption by FeO at the region under the raceway is not taken into account here though it remains the subject for a future study. The experiment is performed using a two-dimensional cold model of forming polymer particles and water with no gas flow. The loci of particle movement during storage/drainage of water are determined in detail. The particle descending velocity in the shaft is found to decrease with floating of the hearth packed bed and increase with the sinking motion. Then, the renewal rate is estimated by subtracting the descending rate from the total particle discharging rate being controlled at constant rate.

For the theoretical confirmation and verification of the issues concerned with deadman motion, the renewal process, renewal rate and the wall normal contact forces at the hearth of the model when storing liquid and following tapping is repeated are also evaluated by means of the numerical treatment called Discrete Element Method (DEM). Since the discontinuity of the stress transmission can be handled easily, recently DEM is widely used to simulate the solid flow problems. Whereas DEM has been applied main-
ly for analyzing the interaction between the solid and gas phases, few analyses can be found on the interaction between solid and liquid phases. In this paper the analysis is carried out by two-dimensional DEM model.

### 2. Experimental Apparatus and the Results

#### 2.1. Experimental Apparatus

Figure 1 shows the two dimensional experimental apparatus of which depth is 6 cm. The model consists of the shaft with the angle 82° to the horizontal and the belly as the dimensions are shown in Fig. 2. Spherical particle of polymer foam, the diameter is 3.24 mm and apparent density is 85.6 kg/m³, was used as packed material and the voidage of the packed bed was 0.42. Supplying and discharging water from bottom of the apparatus was performed to simulate storing and tapping of molten liquid. The density ratio of water to polymer particle is 11 : 1, approximately equal to the ratio of molten iron to coke about 8 : 1. Particles were extracted by the screw feeders at the depth of 20 mm inside each wall. The gas injection from tuyere was not performed. The experimental condition is shown in Table 1. $U_\alpha$ is the particle descending velocity at the top of the model furnace and its standard value is set as 2.42 cm/min, determined referring to the principle of similarity by equalizing the Froude number ($Fr$) in the model and the real furnace as illustrated in the previous work. $G_t$ is the total amount of particle discharging rate by the screw feeders. $W$ and $T$ are the liquid flow rate and the period for storage or drainage, respectively. So many factors such as solid load, wall friction, liquid level difference between start and end of storing molten liquid, hearth depth and so on are related profoundly to the floating mechanism of hearth packed bed as suggested previously. However, non-dimensional groups consisting of those factors for scale up are not considered here except for the density ratio and the Froude number as mentioned above, because the present study concerns clarifying the solid behavior in the case that floating and sinking of hearth packed bed will certainly occur.

#### 2.2. Solid Flow Patterns

Figure 2 shows the steady solid flow pattern, obtained with the colored tracer particles and with no water supply. The lateral and the longitudinal lines are the time lines every interval of 5 min and the loci of the particle movement, respectively. Piston flow, shown by horizontal time lines, is seen in the upper part of shaft, and funnel flow where the share flow of particles is dominant is observed in the lower part of shaft to the outlet for particle discharge. Figure 3 shows the loci of the colored tracer particles when the hearth packed bed repeats floating and sinking with storage and drainage of water, which are described in two pictures for easy comprehension. Lines from the odd number to the even number as 1 → 2 show the particle movement during floating of the particle bed and lines from the even number to the odd as 2 → 3 show the one during sinking. The big symbols show the initial positions of each tracer particle. The solid-free space that is the region occupied by water only appears as the particle bed floats. The height of the free space is approximately uniform in the lateral direction. The location of deadman surface shown in Fig. 3 was invariant during floating of the packed bed. When the packed bed sank with draining water, the surface also moved downwards expanding the converging channel for funnel flow and making some particles intrude in the deadman, in a manner described previously. In the experiment, 3 times of the up-and-down motions were repeated and as the result, the following four types of solid flow pat-

| $U_\alpha$ [cm/min] | $G_t \times 10^6$ [kg/min] | $T$ [h] | $W \times 10^6$ [m³/min] |
|--------------------|-----------------------------|--------|--------------------------|
| 1.21               | 11.8~12.49                  | 2      | 0.56                     |
| 2.42               | 24.62~25.91                 | (a) 4  | 0.28                     |
|                    |                             | (b) 2  | 0.56                     |
|                    |                             | (c) 1  | 1.12                     |
| 4.84               | 46.38~52.77                 | 2      | 0.56                     |
tern were clarified;

(1) Particles near the central axis in deadman go downwards almost vertically repeating the up-and-down motion. They are to be the particles which came in across the top of the deadman.

(2) Particles in the surface layer of deadman are easily pushed out to the funnel flow region when the deadman floats and finally discharged from the outlet.

(3) Particles ranged below the solid outlet level move toward the outlet repeating the zigzag up-and-down motion and discharged from the outlet.

(4) Particles in the deeper position repeat the vertical up-and-down motion only at the same place.

These behaviors are qualitatively in agreement with the previous results by a semi-cylindrical apparatus with gas injection. The sum of the amounts by the terms (2) and (3) should be balanced with that by the term (1).

2.3 Evaluation of the Particle Renewal Rate in Deadman

Here, \( G_1 \) is defined as the particle descending flow rate in the upper part of the shaft. \( G_2 \) the particle renewal rate that is the solid moving rate forced into the solid outlet from the inside of deadman when the hearth particle bed floats, given as the sum of the terms (2) and (3) in the previous section. Then the following equation is derived easily from the material balance:

\[
G_2 = G_1 - G_t \quad \text{(1)}
\]

When the particles descend in the state of piston flow, \( G_t \) can be calculated from the vertical component of the particle descending velocity, \( U_s \), as

\[
G_t = \rho_0 U_s S \quad \text{(2)}
\]

Here, \( S \) and \( \rho_0 \) are the averaged cross section and the bulk density of the packed bed where \( U_s \) is measured. When the solid flow attained steady state about 1 h after the start of the operation, 9 colored tracer particles were horizontally placed in regular intervals at the depth of 5 cm or 10 cm from the top of the apparatus in order to measure the particle velocity.

\( G_2 \) also depends on the value of the bulk density \( \rho_0 \). It is necessary to know how the \( \rho_0 \) changes as the hearth bed moves up and down. When the deadman particles are not renewed (\( G_t = 0 \)), \( \rho_0 \) is calculated from Eqs. (1) and (2) as

\[
\rho_0 = \frac{G_t}{U_s S} \quad \text{(3)}
\]

By Using Eq. (3), \( \rho_0 \) was evaluated in the following states.

State 1: No water was supplied.

State 2: Some water was supplied but the hearth bed did not float yet, that is, the level of the solid-free space was 0. Here, water level was 18 cm immediately before the floating of bed.

State 3: Water was supplied until the level of the solid-free space became 6 cm, the maximum in the experiment, and then its level was kept during the measurement. Water level was 27.5 cm in this case.

Figure 4 shows the change of \( \rho_0 \) with \( G_t \) in these three states. \( \rho_0 \) is approximately constant and its value is about 72.5, which means that the effect of buoyancy on \( \rho_0 \) is negligible small as well as the effect of \( G_t \). Here, the constant value 72.5 kg/m^3 was still assumed even when the bed moves up-and-down. Hence, \( G_1 \) is only the function of \( U_s \) as

\[
G_1 = 72.5 \times 10^{-3} U_s S \quad \text{(4)}
\]

The Figs. 5 and 6 for different value in \( G_t \) show the time variation of \( G_t \) and \( G_2 \) while water is stored (left) and drained (right). These values are put into dimensionless forms by the total amount of particle discharging rate \( G_t \) and the scale for those values is indicated on the left side of the figures. The other scale on the right side is for the levels of water and free space height. While water is supplied, but solid-free space does not appear yet, \( G_t/G_1 \) is kept unity. In
other words, $G_1=0$ and hence, there is no renewal of deadman particles. However, once the particle bed begins to float being forced upwards by buoyancy and the free space appears at the bottom, $G_2$ increases with increasing of the free space height and $G_1$ does decrease. In the case of drainage, $G_2$ begins to decrease rapidly and no particle flow forced from deadman attains. At the same time, $G_1/G_t$ reaches unity, the original value before the bed floats. During draining water or sinking of the bed, new particles would come in across the top of deadman as mentioned before. Total amount of particles forced into the solid outlet from the inside of deadman every floating motion should be equal to that of the new particles every sinking motion. Table 2 shows the minimum value in the descending rate $G_1/G_t$ and the maximum value in the renewal rate $G_2/G_t$ for all the experimental runs. From the table, $G_1/G_t$ decreases to the maximum of 75% $G_2/G_t$ and attains to the maximum of 25% under the conditions of the Run 1 and 2. Further, it is shown that the ratio $G_2/G_t$ would decrease with increasing of $G_t$.

Table 2. Minimum values of $G_1/G_t$ and maximum values of $G_2/G_t$ and $G_t$

| $T$ | Run | $G_t \times 10^3$ | $G_1/G_t$ | $G_2/G_t$ | $G_1 \times 10^3$ |
|-----|-----|-----------------|-----------|-----------|-----------------|
| [h] | No. | [kg/min]       | [ ]       | [ ]       | [kg/min]        |
| 2   | (1) | 12.66          | 0.75      | 0.25      | 3.16            |
|     | (2) | 12.69          | 0.76      | 0.24      | 3.09            |
|     | (3) | 25.08          | 0.65      | 0.15      | 3.76            |
|     | (4) | 24.97          | 0.65      | 0.15      | 3.75            |
|     | (5) | 51.81          | 0.90      | 0.10      | 5.18            |
|     | (6) | 51.62          | 0.90      | 0.10      | 5.17            |
| 1   | (7) | 12.67          | 0.77      | 0.23      | 2.91            |
|     | (8) | 25.12          | 0.87      | 0.13      | 3.27            |
| 4   | (9) | 25.19          | 0.83      | 0.17      | 4.28            |

3. Discrete Element Method (DEM) and the Analytical Model

3.1. Discrete Element Method (DEM)

In Figs. 7 and 8, particles $i$ and $j$ are in contact with each other. In Fig. 7, the normal and tangential components of the contact force are expressed with the Kelvin–Voigt model adding a slider mechanism to the tangential direction. The slider works between particles when the tangential component of the force exceeds the maximum static friction force, and then it is replaced to the dynamic friction force. $\theta$ is the angle between the line passing through the center of the $i$’th particle to the $j$’th particle and the $x$-axis. The counterclockwise rotation is defined as positive.

3.2. The Constitutive Equation

The components of the contact force to the normal and the tangential directions are expressed as

$$f_n = K_n (\Delta l_n^t + l_0^t) + D_n \Delta l_n^t / \Delta t \quad \text{.................(5)}$$

$$f_s = K_s (\Delta l_s^t + l_0^s) + D_s \Delta l_s^t / \Delta t \quad \text{.................(6)}$$

Here, $K_n$ and $D_n$ are the modulus of longitudinal elasticity and the dashpot coefficient in the normal direction, respectively. $K_s$ and $D_s$ are those in the tangential direction. $l_0$ is the relative displacement of particle $i$ to particle $j$. $\Delta l_n$ is the increment of relative displacement in a time step $\Delta t$, respectively. $r_i$ is the radius of $i$’th particle.

The sliding mechanism as mentioned above is expressed in the following equations using the $\mu_s$ and $\mu_d$ as the coeffi-
The buoyancy $F_b$ and the drag forces $D_i$ are introduced when the particles are in liquid as shown in Fig. 10. The buoyancy is assumed to be proportional to the volume of the particle immersed in liquid, $\text{vol}$ (Eq. (10)). The drag force by liquid flow is defined as $\text{Eq. (11)}$ with the drag coefficient $C_D$, the square of the liquid velocity $V$, and the projected area $S_p$ perpendicular to the direction of the particle motion.

$$F_b = \rho_f \cdot \text{vol} \cdot g \quad \text{(10)}$$

$$D_i = \frac{1}{2} C_D \cdot \rho_f \cdot S_p \cdot V^2 \quad \text{(11)}$$

Here, $\rho_f$ is the density of water and $g$ is the gravitational acceleration. The effect of the fluid dynamics of liquid is neglected.

### 3.4. Physical Properties and Dimensionless Parameters

Through the numerical analysis, the elastic modulus and the dashpot coefficient listed in Table 3 are assumed to be constant. The normal or tangential elastic moduli, $K_n$ and $K_t$, and the dashpot coefficient $C_{\text{dp}}$ are referred to the values experimentally determined by Tanaka based on the property of the actual particles in blast furnace. The dashpot coefficient is calculated from the critical damping condition. Table 4 shows the diameter $d_i$ and the mass $m$ of the particle used in the analysis. The density of coke is adopted as the representative particle density for analysis, and every parameter is made dimensionless by the representative values as follows.

$$l_{ij}^{\ast} = \frac{l_{ij}^{l}}{\rho_p} \quad \rho_{ij}^{\ast} = \frac{\rho_{ij}^{l}}{\rho_p} \quad S^{\ast} = \frac{S}{d_p^2} \quad \text{vol}^{\ast} = \frac{\text{vol}}{d_p^3}$$

$$\rho_{ij}^{\ast} = \frac{\rho_{ij}^{l}}{\rho_p} \quad \rho_{ij}^{\ast} = \frac{\rho_{ij}^{l}}{\rho_p} \quad S^{\ast} = \frac{S}{d_p^2} \quad \text{vol}^{\ast} = \frac{\text{vol}}{d_p^3}$$

$$U_{ij}^{\ast} = \frac{U_{ij}}{D_p d_p} \quad U_{ij}^{\ast} = \frac{U_{ij}}{D_p d_p} \quad U_{ij}^{\ast} = \frac{U_{ij}}{D_p d_p}$$

$$f_{ij}^{\ast} = \frac{f_{ij}}{K_{ij} d_p} \quad f_{ij}^{\ast} = \frac{f_{ij}}{K_{ij} d_p} \quad f_{ij}^{\ast} = \frac{f_{ij}}{K_{ij} d_p}$$

$$\text{Eq. (12)} \quad \text{Eq. (13)} \quad \text{Eq. (14)} \quad \text{Eq. (15)}$$

These equations are based on the $i$’th particle and the summation of $j$ shows the sum of the contact forces around the $i$’th particle. $\phi$ is rotation angle and $I$ is the moment of inertia. The equation of motion is analyzed with the numerical treatment coded in the finite difference method.

### 3.3. Equation of Motion

The simulation should be carried out with three-dimensional analysis when requires the rigid solution of solid behavior and then DEM needs enormous amount of calculation. Two-dimensional analysis is considered to be effective when the goal is the qualitative evaluation, though the voidage of two-dimensional packing is so much low that the overestimation of particle contact force might affect the solution. Nevertheless, most advantage of two-dimensional analysis is that the calculation is capable of carrying out with usual personal computer. Thus, the equation of motion is described in two-dimensional Cartesian coordinate in this paper. The components of the translation motions in $x$ and $y$ coordinates and the rotation are expressed as,

$$m_i \ddot{x}_i + \sum_{j} (f_{ij}^{x} \cos \theta_j - f_{ij}^{y} \sin \theta_j) - D_{ij} = 0 \quad \text{(12)}$$

$$m_i \ddot{y}_i + \sum_{j} (f_{ij}^{x} \cos \theta_j - f_{ij}^{y} \sin \theta_j) - mg + F_N - D_{ij} = 0 \quad \text{(13)}$$

$$I \ddot{\phi}_i + \sum_{j} N = 0 \quad \text{(14)}$$

Here, $\text{Fig. 9}$ shows the rotational motion and $\text{Fig. 10}$. The tangential components of the contact forces make the particle rotate, which results in generating the rotational moment $I$ resisting the force with rotational moment $\phi$. The buoyancy $F_b$ and the drag forces $D_i$ are introduced in a form of the rotational moment $I$. The components of the translation motions in $x$ and $y$ coordinates and the rotation are expressed as.
In the following numerical analysis, the asterisk mark showing dimensionless quantity is omitted as long as there is no confusion.

4. Numerical Analysis

4.1. Analytical Model of Blast Furnace and Conditions

Figure 11 shows the dimensions of analytical model of blast furnace. A half side region is used for the calculation. The dimensionless height of the furnace divided by the particle diameter is 115, and the bottom width is 20. The shaft angle is 82° and the raceway is simulated by the particle discharging region, defined as the inspection area with dimensionless $\frac{6}{H_1}$ square in Fig. 11. The numbers of the particles in the inspection area are counted in every time step, and the particle nearest to the left boundary of the inspection area is taken off and returned to re-charge at the top of the furnace. In the analysis, the dimensionless time of 1 638 equals to 1 s for the real time, and the particle-discharging rate from the raceway is controlled as 50 or 100 particles per second. Since the present method was not capable of forming static deadman in the state of steady flow when no friction was imposed on the axially symmetric wall (center boundary), imposing the wall condition giving some friction was innovated. The technique was effective for deadman to keep a suitable height in a quasi-stagnant state. Here, deadman is defined as the region in which the vertical component of the particle moving length for the dimensionless time of 8 190 (5 s) is less than 1, in other words, the moving rate less than about 0.2% or 0.4% the total particle-discharging rate.

4.2. Initial Distribution of the Particles

The figure on the right hand side in Fig. 11 shows the initial distribution of particles, charged with a random free fall from the top of the apparatus. The diameters of the particles are varied among the dimensionless lengths of 0.8–1.0 by using the random function. Analytical conditions are shown in Table 5.

4.3. Accumulation and Tapping Conditions of the Liquid

Two types of liquid density were chosen for discussing the effect of buoyancy, that is, 10 and 20 times the particle density as shown in Table 5. The dimensionless total volume of the liquid for storage is 100, which is correspondent to dimensionless height of 5 for the empty container with the width of 20. In the current calculation, dimensionless times for storing up and tapping off the liquid are the same, that is, 24 570 for the condition 1 and 32 771 for the condition 2, respectively. The operation for storage of the liquid was performed after the particle movement was regarded as the steady state. The inflow or outflow rates of the liquid were kept constant during the analysis and the analysis was continued with no interval between end of storage and start of tapping.

5. Analytical Results and Discussion

5.1. Flow Pattern

Figure 12 shows the flow pattern at each dimensionless time for the condition 1. In the figure, $T_1$ and $T_2$ indicate start time and end time of storage, respectively. $T_3$ and $T_4$ are those for the second operation. A funnel flow region is observed below the lower part of the shaft where the velocity lag is considerable near the walls, which is in qualitative agreement with the experimental shown in Fig. 2. The results obtained numerically are summarized by the following topics.

1. The liquid level rises in proportion to the progress of time, but the packed bed floating does not occur until the liquid level reaches at a certain height. The solid-free space region occupied by the liquid only, appears above the bottom of the model after the packed bed begins to float.

2. Until the end of storage $T_2$, the amount of the particles that have been occupied in the region below the raceway level decreases. The reduction is due to the consumption in the raceway being forced by floating motion of the packed bed.

3. Particles just at the raceway level at the end of storage descend into deeper region by the following liquid tapping.

4. From the observation of the particle flow patterns in each time, the particles mainly come to fill the deadman.
from an limited area near the right wall. These characteristic behaviors are examined more precisely in the following section.

5.2. Particle Movements in Deadman with Storing and Tapping Liquid

Under the condition 1, the particle movements in deadman with storing and tapping liquid is shown in Fig. 13. In the figure, open diamond mark (○) indicates the initial locations when the first storage starts. The loci of the particle movement with time are described in twice the storing and tapping operations. The open (○) and solid (●) circles mean the starts of storing and tapping liquid, respectively. The loci are shown connecting simply the open and solid circles. These simulated particle flow patterns are fairly well in qualitative agreement with the experimental results shown in Fig. 3. The results obtained here can be characterized in four types of particle movements; (1) Particles in the surface layer of deadman are pushed out to the solid funnel flow region or the raceway. (2) Particles in the middle part of deadman moves toward the raceway with zigzag motion. (3) The particles near the central axis (i.e., right wall) above the top of deadman come in to fill deadman, descend vertically with up-and-down motion and contribute to renew the particles in deadman. (4) Particles in deeper region near the bottom repeat up-and-down vertical motions only at almost same location.

Figure 14 indicates the enlargement of the loci of the particle movements in the surface layer and the middle part of deadman under the condition 2. In this condition, the liquid density is much lower than in the condition 1, that is, the free space height is reduced because of less buoyancy effect. However, the flow patterns are almost same as in the condition 1 except for that the particle movement is much slower with the smaller amplitude of up-and-down motion. This situation might be more close to the real motion. In such a case, particles in the actual deadman could be renewed in a small floating and sinking motion but in many repetitions. The numerical results given by Figs. 13 and 14 also simulate qualitatively the experimental ones obtained with a semi-cylindrical cold model with air injection.\(^3\)

Figure 15 describes the upstream locations of particles which have renewed deadman for the condition 1. The open circles (○) mean the particle locations just at the start of liquid storage, the gray solid symbols just after the end of storage and the black solids (●) at the end of liquid tap-
ping. Two pictures in Fig. 15 are for confirming the reproducibility. This result clarifies that only the particles charged near the center area at the top of model furnace can go down into deadman and contribute the renewal of the deadman. The numerical analysis verifies more clearly and precisely the phenomenon which has been reported by the experiments.1–3)

Figure 16 shows the changes of the ratios $G_2/G_t$, $G_1/G_t$ and the height of the free space during storing/tapping liquid comparing the numerical result with the experimental one. The upper figure is the numerical result and the lower is the experimental one that is the same as Fig. 5. In the numerical, deadman renewal rate $G_2$ were calculated by counting number of the particles pushed out from deadman during the dimensionless time of 819 and then $G_1$ was calculated from Eq. (1). The particle descending rate $G_1$ decreases and the renewal rate $G_2$ increases as the hearth packed bed floats, and the behavior is in good agreement with the experiment.

Figure 17 shows the distribution of the wall normal contact force along the left side wall of model furnace while the motion of packed bed floating and sinking is repeated. In the figure, $T_1$ and $T_2$ again indicate the starting and ending times for liquid storage, $T_3$ and $T_4$ are those for the second time. The wall contact force in the hearth of the model increases gradually as the hearth packed bed floats and decreases as it sinks with tapping liquid. The increase of the wall contact force is seemed due to that deadman particles are compressed by both the downward solid load and upward force by floating of packed bed. This phenomenon is
correspondent to the passive state of stress in which a large horizontal stress is generated on the wall of converging container for particulate material under the gravity flow. On the contrary, the decrease of the wall contact force is correspondent to the active state of stress in which the stress in the vertical direction is larger. Judging from this result, the assumption that a critical stress field for deadman and hearth packed bed being immediately before the transition from static to floating state is in an active state of stress is seemed appropriate. Here, important thing is that the repletion of such an increase of wall contact force would lead to hearth wall abrasion.

6. Conclusions

Particle flow pattern in the iron making blast furnace with floating of the hearth packed bed as the molten liquid is stored in the hearth and sinking as the liquid is tapped were investigated by two dimensional experimental and DEM analyses. As a result of both the experimental and numerical treatment, it is visualized that particles in deadman move gradually to the outlet called raceway while hearth packed bed repeats floating and sinking in the liquid. The particle motions found are classified in four types of movement depending on the particle location in deadman. More importantly, the particle descending velocity in shaft decreases and the renewal rate of deadman particles increases as the hearth bed floats. This renewal motion consists of that older particles go out of deadman while the packed bed floats and the newer comes in to fill deadman during tapping liquid. The older particles in the surface layer of deadman are found to be renewed easily and rapidly with the up-and-down motion. But even in the deeper region of deadman, particles are renewed gradually. The numerical analysis clarifies that the new particles are to come in the deadman mainly through a limited area near the top of deadman. In the hearth part, the wall normal contact force evaluated numerically increases considerably when the hearth packed bed floats and decreases when it sinks.

Nomenclature

- \( b \): Particle contact length, defined in Fig. 9 (m)
- \( C_D \): Drag coefficient by liquid flow (\( \frac{\text{N} \cdot \text{s}}{\text{m}} \))
- \( D \): Dash pot coefficient (\( \frac{\text{N}}{\text{s/m}} \))
- \( d_p \): Particle diameter set up in numerical analysis (m)
- \( D_r \): Fluid drag force acting on a particle (N)
- \( f_{ij} \): Contact force acting between the \( i \)’th and the \( j \)’th particles (N)
- \( f \): Sum of the contact forces acting on the \( i \)’th particle (N)
- \( G_1 \): Particle descending rate in upper part of model furnace
  - Experiment (kg/min), Numerical analysis (–)
- \( G_2 \): Particles renewal rate in deadman
  - Experiment (kg/min), Numerical analysis (–)
- \( G_t \): Total particle discharging rate by screw feeders
  - Experiment (kg/min), Numerical analysis (–)
- \( g \): Gravitational acceleration (m/s²)
- \( I \): Moment of inertia (kg · m²)
- \( K \): Elastic modulus (N/m)
- \( l_0 \): Relative displacement of particle \( i \) to particle \( j \) (m)
- \( m \): Mass of a particle (kg)
- \( N \): Number of particle packed in bed (Number)
- \( N_s \): Number of particle packed in bed
  - Experiment (kg/min), Numerical analysis (–)
- \( N_r \): Rotational friction force resisting the moment \( N_p \) (N · m)
- \( N_{r0} \): Number of particle packed in bed (Number)
- \( N_{r1} \): Moment caused by \( f_c \), which is the sum of tangential stresses acting on \( i \)’th particle (N · m)
- \( r \): Radius of particle (m)
- \( S \): Mean cross sectional area of shaft where \( U_j \) is measured (m²)
- \( S_n \): Projected area of a particle immersed in liquid, defined in Fig. 10 (m²)
- \( T \): Time for storing/tapping of liquid (h)
- \( T_1, T_2 \): Dimensionless start and end time for the first storage of liquid (–)
- \( T_{1p}, T_{1s} \): Dimensionless start and end time for the second storage of liquid (–)
- \( T_F \): Free space level in each time in Fig. 3 (m)
- \( t \): Time (s)
- \( U_{so} \): Particle descending velocity at the top of the model furnace (cm/min)
- \( U_{so} \): Particle descending velocity averaged in the upper inspection area (cm/min)
- \( V \): Particle velocity in liquid (m/s)
- \( V_l \): Liquid volume for storage (m³)
- \( V_{vol} \): Particle volume immersed in liquid (m³)
- \( W \): Storing/tapping rate of liquid (m³/min)
- \( W_t \): Total particle discharging number (Numbers)
- \( \dot{x} \): Acceleration component to the \( x \)-axis direction (m/s²)
- \( \dot{y} \): Acceleration component to the \( y \)-axis direction (m/s²)

Fig. 17. Change of vertical distribution of wall contact force with storing/tapping liquid (Condition 1).
Greek letters
Δl_{ij}: Increment of relative displacement between the i’th and the j’th particles in a time step Δt (m)
Δt: Dimensionless step time (−)
θ: Particle contact angle (rad)
μ: Coefficient of friction (−)
μ_{dp}: Coefficient of dynamic friction between particles (−)
μ_{dw}: Coefficient of dynamic friction between particle and wall (−)
μ_{sp}: Coefficient of static friction between particles (−)
μ_{sw}: Coefficient of static friction between particle and wall (−)
ρ_0: Bulk density of packed bed (kg/m³)
ρ_l: Density of liquid (kg/m³)
ρ_p: Particle density set up in the numerical analysis (kg/m³)
φ: Particle rotation angle (rad)
ϕ: Particle angular velocity (rad/s)

ϕ̈: Particle angular acceleration (rad/s²)

Subscripts
i: i’th particle
j: j’th particle
n: Normal direction
s: Tangential direction
w: wall
*: Dimensionless

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