Effect of Particle Penetration Depth on Solid/Liquid Mass Transfer Rate by Particle Blowing Technique

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In this study, cold model experiments on particle blowing were carried out to clarify the effect of particle penetration depth on solid/liquid mass transfer rate. A comparison of penetration depth obtained by experiment and CFD calculation using commercially available software was also carried out. The penetration depth was measured by a visual observation whereas the solid/liquid mass transfer rate was obtained from the ion-exchanged reaction between Na^+ on pearlite particles and H^+ in HCl aqueous solution. Both of the penetration depth and solid/liquid mass transfer rate increased with the increase in particle feed rate and top blowing gas flow rate, and the decrease in lance height and particle diameter. The following non-dimensional equation of particle penetration depth was obtained by several non-dimensional numbers:

$$Re_P = 187Fr^{0.673}We^{0.199}\left(\frac{\rho_l - \rho_p}{\rho_l}\right)^{0.447}$$

where, Re_P : particle Reynolds number, Fr : Froude number, We : Weber number, ρ_l and ρ_p : liquid and particle densities (kg/m^3), respectively. A good agreement was confirmed by the experiment. The particle penetration depth was also calculated by a combination of VOF and DEM model and it was in good agreement with the experiment. The solid/liquid mass transfer coefficient calculated by the CFD simulation and Froessling equation increased with the increase in top blowing gas flow rate, particle feed rate and penetration depth. The solid/liquid interfacial area was expressed by a function of penetration depth.

KEY WORDS: solid/liquid mass transfer; penetration depth; particle blowing; powder blowing.

1. Introduction

Pulverized flux blowing to molten steel surface accelerates impurity removal rate and its technique has been always developed in the field of steelmaking. For example, the LD-AC process¹⁾ was applied to dephosphorization of molten iron with high phosphorus level by blowing CaO-based powder through a top lance in the converter. A procedure for refining ultra-low sulfur steel by blowing desulfurizing agent on the molten steel in the vacuum vessel of RH degasser has been put to practical use.^{2,3)} Nitrogen removal with decarburization was increased under reduced⁴⁾ or ordinary⁵⁾ pressure by blowing oxidizing flux. Copper and tin removal⁶⁾ rate in molten scrap was enhanced by using oxidizing powder by a combination of plasma heating. Sulfur and oxygen contents affected nitrogen removal during CaO powder blowing under reduced pressure.⁷⁾ On the other hand, the copper smelting and converting process by blowing air, raw material and flux through top lances named as the Mitsubishi process^{8,9)} has been put into opera-

tion since 1974.

The contact time between solid powder and steel melt in the RH degasser is relatively long because the powder blown in the vacuum vessel transfers and suspends in the ladle and finally floats on the steel surface.¹⁰⁾ However, for the powder blowing in the furnace, the contact time when the powder penetrates the interface between gas and steel melt and floats completely on the surface is short compared with the RH blowing. From the view point of the reaction time between powder and steel melt, it is necessary to penetrate powder more deeply in the steel melt and assure the longer contact time. However, there was little research on the relationship between the solid/liquid reaction rate and the penetration depth of the particle into steel melt, although the critical condition and depth of powder penetration were investigated by using hot and cold model experiments.^{11–20)} The trajectory of the solid particle⁹⁾ and inclusion agglomeration²¹⁾ of RH degasser were calculated by a coupled analysis using Navier-Stokes equation and solid particle (inclusion) equation of motion with respect to computation fluid dynamics (CFD) on solid particle behavior in liquid. However, it was difficult to find the research on the penetration behavior of particles or powders by using CFD.

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In this study, cold model experiments were carried out to clarify the effect of the particle penetration depth on the solid/liquid mass transfer rate in parallel with the comparison of the penetration depth between the experiment and calculation by CFD.

2. Experiment and Calculation

2.1. Measurement of Penetration Depth

The schematic diagram of the experimental apparatus for measuring particle penetration depth is shown in Fig. 1. Ion-exchanged water or 3.0 M KCl aqueous solution was put into an acrylic vessel of 400 mm in inner diameter and 400 mm in height so as to have a 100 mm in static bath depth. Liquid and solid densities as well as liquid viscosity used for the experiment are shown in Table 1. Pearlite or polystyrene in a particle feeder (Island Industry Co., Ltd.) was blown in the liquid through a top lance with inner diameter of 13 mm. Air compressed by a compressor (Anest Iwata Corp., SLP-37EB) and controlled by a mass flow controller (MFC) (Yamatake Corp., CMQ-V) was used as a carrier gas for solid particles. In order to compare with the particle blowing, the particle injection experiment was also carried out by immersing the lance into the liquid. A video camera (Sony Corp., HDR-CX700V) was used to measure particle penetration depth. The mean value of 10 measurements was taken as the penetration depth. The experimental conditions of the particle blowing and injection are shown in Tables 2 and 3, respectively. Top blowing gas flow rate, lance height, pearlite and polystyrene feed rates were varied for the particle blowing method, whereas top blowing gas flow rate,

Fig. 1. Schematic diagram of the experimental apparatus for measuring penetration depth.

Table 1. Density and viscosity of liquid and solid used for the experiment.

Liquid or solid	Density (kg/m ³)	Viscosity (Pa·s)
Ion-exchanged water	1.00×10^3	1.00×10^{-3}
3.0 M KCl aq	1.11×10^3	1.02×10^{-3}
Pearlite	1.00×10^2	—
Polystyrene	1.04×10^3	—

injection depth and pearlite feed rate were changed for the particle injection. No polystyrene was used for the injection experiment. Both of top blowing gas flow rate and pearlite feed rate for the particle blowing method were larger than those for the injecting one.

2.2. Measurement of Solid/Liquid Mass Transfer Rate

Figure 2 shows the schematic diagram of the experimental apparatus for measuring solid/liquid mass transfer rate. Air was injected into liquid through a nozzle of 3 mm in diameter at the bottom center of the same vessel as shown in Fig. 1. Before the experiment, pearlite of $d_p = 2.0$ mm in diameter was immersed into 2.0×10^{-3} M NaOH aqueous solution for 12 h, washed by ion-exchanged water until the electric conductivity was kept constant and dried at room temperature for 12 h. After putting 0.25 L of prepared

Table 2. Experimental conditions of particle blowing.

Item	
Top blowing rate, Q_{TB} L/min (STP)	100, 150, 200
Bottom blowing rate, Q_B L/min (STP)**	5
Lance height, LH mm	50, 100, 150
Pearlite feed rate, F_{pl} g/min	28.8, 57.6, 86.4, 115.2
Pearlite diameter, d_p mm	1.3*, 2.0
Polystyrene feed rate F_{ps} g/min*	61.2, 120.6, 178.8, 239.6
Polystyrene diameter, d_p mm*	1.1
Liquid	KCl aq*, HCl aq**

*, only penetration depth, **, only solid/liquid mass transfer

Table 3. Experimental conditions for particle injection.

Item	
Gas injection rate, Q_{Ti} L/min (STP)	50, 80
Bottom blowing rate, Q_B L/min (STP)**	5
Injection depth, ID mm	10, 25
Pearlite feed rate, F_{pl} g/min	3.1, 6.1, 9.5, 12.9
Liquid	Ion-exchanged water*, HCl aq**

*, only penetration depth, **, only solid/liquid mass transfer

Fig. 2. Schematic diagram of the experimental apparatus used for measuring solid/liquid mass transfer rate.

pearlite particles and 12.6 L of 2.35×10^{-4} M HCl aqueous solution into the vessel, particles through the top lance were blown in the liquid with the carrier gas. As H^+ in HCl aqueous solution reacts with Na^+ on the pearlite surface under the rate-determining step of solid/liquid mass transfer,^{22,23)} mass transfer rate can be calculated from the temporal change in H^+ . The concentration of H^+ was measured by an electrical conductivity meter (Automatic system research, mk-250EC) shown as EC in Fig. 2. The injection experiment was also made for the comparison. The experimental conditions of the particle blowing and injecting methods are also shown in Tables 2 and 3, respectively. The operating factors such as top blowing gas flow rate, lance height and pearlite feed rate were changed similar to the penetration depth measurement described in the previous section. To compare with the above methods, the gas blowing without particles was carried out by floating particles on HCl aqueous solution before the experiment. The floated pearlite was changed between 0.15 L (15 g) and 0.87 L (87 g), and top blowing gas flow rate and lance height was fixed to 200 L/min (STP) and 50 mm, respectively.

2.3. Measurement of Pearlite Velocity at Top Lance Exit

For the application to the CFD calculation, the pearlite velocity at the exit of the top lance was measured by a high speed camera (HAS-550, DITECT Corporation). Sampling speed was set to 500 frames/s. Top blowing gas flow rate was varied to 100, 150 and 200 L/min (STP) and pearlite feed rate was fixed to 28.8 g/min. The pearlite velocity ratio to carried air one is shown in Fig. 3. The pearlite velocity was kept to about 30% of the carried air velocity, although the carried air velocity was changed in this study. Generally, the particle velocity ratio to the carried gas depends on various conditions²⁴⁾ such as particle density, diameter and the particle running distance until the exit. In this study, the 30% of the carried gas velocity was set for the particle velocity in the CFD calculation described in Section 2.4 due to the equal particle running distance between the experiment and calculation.

2.4. CFD Calculation

Discrete element method (DEM)²⁵⁾ which can treat collision and repulsion between particles was applied to analyze

Fig. 3. Effect of gas velocity at lance exit on the ratio of particle velocity to carrier gas velocity.

the particles behavior. The equation of particle motion in the fluid is expressed by

$$m \frac{dV}{dt} = F_{\text{drag}} + F_{\text{pressure}} + F_{\text{virtual mass}} + F_{\text{gravitation}} + F_{\text{contact}} \dots (1)$$

where m : mass of a particle (kg), V : particle velocity vector (m/s), F_{drag} , F_{pressure} , $F_{\text{virtual mass}}$, $F_{\text{gravitation}}$ and F_{contact} : drag, pressure, virtual mass, gravitation and contact forces, respectively.

The elastic force and viscous damping in the F_{contact} term was considered without particles rotation and friction.

For the fluid field of particles moving, three-dimensional unsteady incompressible flow in a vessel was calculated with VOF (Volume of Fluid) method. The realizable k - ω model²⁶⁾ was used for the turbulence model. The equations of continuity and motion which control the fluid flow are expressed by Eqs. (2) and (3), respectively.

$$\frac{\partial \rho}{\partial t} + (\nabla \cdot \rho \mathbf{u}) = 0 \dots \dots \dots (2)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + [\nabla \cdot \rho \mathbf{u} \mathbf{u}] = -\nabla p + \mu_{\text{turb}} \nabla^2 \mathbf{u} + \rho \mathbf{g} \dots \dots \dots (3)$$

$$\rho = \alpha_l \rho_l + \alpha_g \rho_g \dots \dots \dots (4)$$

Here, ρ , ρ_l , and ρ_g are the mean, liquid and gas densities (kg/m^3), respectively, $\mathbf{u}$ is the velocity vector (m/s), p is the pressure (Pa), μ_{turb} is the turbulent viscosity ($\text{Pa} \cdot \text{s}$), $\mathbf{g}$ is the gravity acceleration vector (m^2/s), and α_l and α_g are the volume fraction of liquid (water) and gas (air), respectively.

ANSYS Fluent 17.0 (ANSYS, Inc.) was used for the calculation of coupling the DEM model for the particles with the VOF method for the fluid behavior. The particles obtained the external forces in Eq. (1) such as the drag and buoyancy from the fluid, whereas the fluid exchanged the momentum through the particle drag force. Continuum Surface Force method (CSF)²⁷⁾ which dealt with surface tension was applied to calculate the gas/liquid interface of the VOF method, although the interfacial tension between the particle and fluid was not considered.

Pearlite of $d_p = 2.0$ mm in diameter or polystyrene with the carrier gas of air in Table 1 was blown to 3 M KCl aqueous solution. The geometric configuration was the same as the experiment as shown in Fig. 1. Total mesh number was 306 300 and the minimum mesh width 0.6 mm. All of the meshes were composed of hexahedral configuration. The time step for the calculation of the particles movement was 10^{-5} s, whereas that of the fluid was 10^{-3} s. 100 times itera-

Fig. 4. Schematic diagram of particle blowing position at lance exit.

Fig. 5. Comparison of pearlite penetration between CFD calculation and experiment ($Q_{TB}=100$ L/min (STP), $LH=50$ mm).

tions of particles calculation by Eq. (1) were carried out by using a fixed fluid field calculated by Eqs. (2) and (3). Wall function was used at the vessel bottom and wall boundary, and the fluid flowed out at the constant pressure at the vessel top boundary. As shown in Fig. 4, particles were blown vertically through the lance exit and the particle feed rate was controlled by the time interval of injection. There was no velocity distribution at the lance exit.

3. Results and Discussion

3.1. Effect of Operating Factors on Particle Penetration Depth

3.1.1. Particle Blowing

(a) Gas/liquid interface and particle penetration depth

An example of the pearlite penetration behavior compared between the CFD calculation and experiment is shown in Fig. 5. Top blowing gas rate, Q_{TB} , was 100 L/min (STP), top lance height, LH , 50 mm and pearlite feeding rate, F_{PI} , 28.8, 86.4 and 115.2 g/min. The dotted line of the right hand side indicated the interface between gas and liquid confirmed by the visual observation, although it was a little bit difficult to judge the border in this photograph. As for the left hand side image, the small circles were the blown particles. The calculated particle penetration depth into liquid agreed well with the experiment.

Ozawa *et al.*¹²⁾ presented the critical particle penetration velocity into liquid as follows:

$$V_c^2 = \frac{\gamma_{gl}}{r_p^2 \rho_l} \cdot \frac{1}{0.044} \left\{ \left(1 - \exp \left(\frac{0.66}{\rho_p / \rho_l + 1/4} \right) \right) \left(\frac{\rho_p / \rho_l + 1/4}{0.33} - 1 + \cos \theta_c \right) + 2 \right\} \quad \text{..... (5)}$$

where V_c : critical penetration velocity of particle (m/s), γ_{gl} : surface tension of water ($=7.3 \times 10^{-2}$ N/m)²⁸⁾, r_p : particle radius (m), θ_c is the contact angle ($=0^\circ$ for pearlite, 90° for polystyrene). The pearlite was calculated to penetrate at every particle velocity due to the negative value of the right side in Eq. (5) and the critical penetration velocity of polystyrene became 0.294 m/s. As the minimum polystyrene particle velocity in Table 1 was 12.5 m/s, this experimental condition satisfied the particle penetration condition shown by Ozawa *et al.*¹²⁾

(b) Effect of operating factors on particle penetration depth

The experimental relationship between the polystyrene

Fig. 6. Relationship between polystyrene penetration depth and feed rate for particle blowing.

penetration depth and feed rate is shown in Fig. 6 where (a); top blowing gas flow rate, Q_{TB} L/min (STP), is varied under the constant lance height, LH , and (b); LH is changed and Q_{TB} is fixed. The penetration depth increased with the increases in the polystyrene feed rate and the top blowing gas flow rate and the decrease in the lance height except LH of 100 and 150 mm for polystyrene feed rate of 61.2 g/min. Thus, the penetration depth is roughly enhanced by the hard blowing.

The experimental relationship between the pearlite penetration depth and feed rate is shown in Fig. 7 where (a); Q_{TB} and d_p are varied and LH is fixed, and (b); LH and d_p are changed under the constant Q_{TB} . As well as the polystyrene particles in Fig. 5, the pearlite penetration depth increased with the increase in the feed rate and the top blowing gas flow rate, and the decrease in the lance height. As for the particle diameter, the smaller particle has the larger penetration depth.

Fig. 7. Relationship between pearlite penetration depth and feed rate for particle blowing.

We tried to express the experimental particle penetration depth in terms of the following non-dimensional numbers.

$$Re_p = \frac{\rho_l N L_p d_p'}{\mu} \dots\dots\dots (6)$$

$$We = \frac{\rho_l L_p^3 N^2}{\gamma_{SL}} \dots\dots\dots (7)$$

$$Fr = N \sqrt{\frac{L_p}{g}} \dots\dots\dots (8)$$

where Re_p : particle Reynolds number, We : Weber number, Fr : Froude number, γ_{SL} : interfacial tension (N/m), N : number of particles per second (s^{-1}), L_p : penetration depth (m), d_p' : particle diameter (m), g : gravitational acceleration (m/s^2), μ : viscosity (Pa·s). Equation (9) was obtained from the multiple regression analysis using the above non-dimensional numbers and the density difference normalized by liquid density.

$$Re_p = 187 Fr^{0.673} We^{0.199} \left(\frac{\rho_l - \rho_p}{\rho_l} \right)^{0.447} \dots\dots\dots (9)$$

where ρ_p is the particle density (kg/m^3). The correlation result is shown in Fig. 8. The correlation coefficient was $R^2=0.995$.

The experimental penetration depth was compared with the calculated value obtained from the CFD as shown in Fig. 5. The results are shown in Fig. 9. The experimental values agreed with the CFD calculation in spite of no γ_{sl} term for the CFD calculation. It seems to be due to the low power

Fig. 8. Correlation among non-dimensional numbers.

Fig. 9. Comparison between CFD calculated and experimental penetration depth.

(= 0.199) of Weber number in Eq. (9) and the correlation may be changed for the wide range of γ_{sl} .

On the other hand, Kimura¹¹⁾ proposed an empirical equation of particle penetration depth including cavity depth as follows:

$$H_p = 0.136 d_{PK}^{1.266} U_{SK}^{0.135} \rho_{IK}^{-0.609} \rho_{SK}^{0.12} N_{PK}^{0.494} U_{CK}^{0.182} (d_{OK} + 2H_{OK} \tan \theta)^{0.475} \dots\dots\dots (10)$$

$$N_{PK} = W_{SK} / \frac{\pi}{6} d_{PK}^3 \rho_{SK} S_{OK} \cdot 10^{(A-2)} \dots\dots\dots (11)$$

$$A = 1.091 - 0.999 (\log(H_{OK} / d_{OK}))^2 + 1.4623 \log(H_{OK} / d_{OK}) - 0.0843 \log(U_{CK} / 100) + 0.253 \log(W_{SK} / S_{OK}) \dots\dots\dots (12)$$

where H_p : particle penetration depth including cavity depth (cm), d_{PK} : particle diameter (cm), U_{SK} : particle velocity at the lance exit (cm/s), ρ_{IK} : liquid density (g/cm^3), ρ_{SK} : particle density (g/cm^3), N_{PK} : number of particles per unit gas jet volume defined as Eq. (11) ($1/cm^3$), U_{CK} : gas axial velocity (cm/s), d_{OK} : lance inner diameter (cm), H_{OK} : lance height (cm), θ : gas jet cone angle (= 4.6 deg), W_{SK} : particle feeding rate ($g/cm^3 s$), S_{OK} : nozzle sectional area (cm^2), A : defined by Eq. (12). Figure 10 shows the rela-

Fig. 10. Comparison between calculated H_p by the empirical expression of Kimura¹¹⁾ and experimental one.

Fig. 11. Relationship between penetration depth and pearlite feed rate for particle injection.

relationship between the calculated H_p by Eqs. (10)–(12) and the experimental one. The calculation could not explain the experimental results, although the calculated H_p values increased with the increases in the particle feed rate for each top blowing gas flow rate and lance height. The difference between the calculation and experiment resulted from the multiple regression equation with dimensional terms.

3.1.2. Particle Injection

To compare the penetration behavior of particles injection into water through the immersed lance with that of the particle blowing, the particle penetration depth of the injection was examined. The relationship between the particle penetration depth and feed rate is shown in Fig. 11. The penetration depth increased with the increase in the feed rate and the gas injection rate, Q_{Ti} (L/min), but was not dependent on the lance immersion depth, ID (mm). Compared with the particle blowing in Figs. 6 and 7, the penetration depth of the particle injection was smaller, because the pearlite feed rate was smaller than that of top blowing.

3.2. Effect of Operating Factors on Solid/liquid Mass Transfer Rate

3.2.1. Calculation of Solid/liquid Mass Transfer Coefficient

Ion exchanged reaction of pearlite with Na^+ is expressed by Eq. (13).

As the reaction rate is normally controlled by the diffusion in the fluid film at the early stage,^{22,23)} solid/liquid mass transfer rate during pearlite blowing is given by Eq. (14).

$$-VdC/dt = (k_1a_1 + k_2a_2)(C - C_i) \quad \dots\dots\dots (14)$$

where, V : volume of HCl aq (m^3), C : HCl concentration ($kmol/m^3$), t : reaction time (s), k_1 : solid/liquid mass transfer coefficient at the particle blowing spot (m/s), a_1 : total surface area of pearlite particles at the particle blowing spot (m^2), k_2 : solid/liquid mass transfer coefficient of the floated particles on HCl aq. surface (m/s), a_2 : total surface area of pearlite particles floated on HCl aq. surface which exists initially and move away from the particle blowing spot (m^2), C_i : HCl concentration at the pearlite/HCl aq ($kmol/m^3$). With the assumption that C_i equals to be 0,^{29,30)} and both a_1 and a_2 are independent of time, integration of Eq. (14) became Eq. (15), where C_0 : initial HCl concentration ($kmol/m^3$).

$$\ln(C_0/C) = [(k_1a_1 + k_2a_2)/V]t \quad \dots\dots\dots (15)$$

An example of temporal change in C_0/C is shown in Fig. 12. Q_{TB} was 200 L/min, LH is 50 mm and pearlite feed rate, F_{PI} was 86.4 g/min. As logarithmic C_0/C increased almost linearly with time, the slope became the constant $(k_1a_1 + k_2a_2)/V$ value. The linearity of $\ln(C_0/C)$ was also obtained at the other particle blowing condition in this study.

3.2.2. Particle Floated on Liquid

Solid/liquid mass transfer rate was studied when pearlite particles were floated on the surface of HCl aqueous solution with the gas blowing without particle. Total surface area, a_2 (m^2), of floated pearlite particles was calculated by Eq. (16).

$$\begin{aligned} a_2 &= \pi d_p^2 N_2 = \pi d_p^2 m_2 / m_0 \\ &= \pi d_p^2 m_2 / (\pi d_p^3 \rho_p / 6) = 6m_2 / (d_p \rho_p) \quad \dots\dots (16) \end{aligned}$$

where, N_2 : number of floated particles, m_2 : mass of floated particles (kg), d_p : 2.0×10^{-3} m, m_0 : mass per a particle (kg). Thus, k_2 is obtained by substituting a_2 into Eq. (15).

The relationship between k_2 and mass of pearlite is shown in Fig. 13. Q_{TB} and Q_B were 200 and 5 L/min (STP), respectively, and LH was 50 mm. The increasing mass of floated particles reduced the k_2 value, because thicker particles layer

Fig. 12. Typical example of temporal change in hydrochloric acid concentration.

Fig. 13. Relationship between mass transfer coefficient and mass of pearlite floated on liquid.

Fig. 14. Relationship between mass transfer capacity coefficient and pearlite feed rate for particle blowing.

became insufficient to contact between the pearlite particle and HCl aqueous solution.

3.2.3. Particle Blowing

The particle blowing might enhance the floated particles temporally and the solid/liquid mass transfer rate due to the increasing a_2 . However, as seen in the slope in Fig. 12, the linearity of the slope was confirmed, that is, $(k_1a_1 + k_2a_2)/V$ was kept constant. In this study, it means that

$$k_1a_1 \gg k_2a_2 \dots\dots\dots (17)$$

The relationship between mass transfer capacity coefficient and pearlite feed rate is shown in Fig. 14 where (a) is under the varied Q_{TB} (L/min) and the constant LH , and

Fig. 15. Segmentation for obtaining liquid and particle velocities.

(b) is under the varied LH and the fixed Q_{TB} . As well as the penetration depth in Figs. 6 and 7, the k_1a_1/V value increased with the increasing pearlite feed rate and top blowing gas flow rate, and the decreasing lance height.

We assumed that the solid/liquid mass transfer occurred mainly from the particle breakthrough point at the cavity until the deepest particle penetration position. Froessling equation³¹⁾ expressed by Eq. (18) is widely used to analyze the solid/liquid mass transfer rate in the fluid.

$$Sh = 2 + 0.6Re_p^{1/2}Sc^{1/3} \dots\dots\dots (18)$$

$$Sh = \frac{k_1d_p}{D} \dots\dots\dots (19)$$

$$Re = \frac{\rho_l |\overline{v_p}| d_p'}{\mu} \dots\dots\dots (20)$$

$$Sc = \frac{\mu}{\rho_l D} \dots\dots\dots (21)$$

where Sh : Sherwood number, Re : Reynolds number, Sc : Schmidt number, $|\overline{v_p}|$: absolute value of relative velocity between particle and liquid (m/s), D : diffusion coefficient (m^2/s).

The $|\overline{v_p}|$ values were obtained from the results of the CFD simulation by Eq. (22).

$$|\overline{v_p}| = \sqrt{(v_{px} - v_{lx})^2 + (v_{py} - v_{ly})^2 + (v_{pz} - v_{lz})^2} \dots\dots (22)$$

where v_{px} , v_{py} , v_{pz} : particle velocities of x, y and z axes of coordinate calculated by CFD analysis, respectively, v_{lx} , v_{ly} , v_{lz} : liquid velocities of x, y and z axes of coordinate calculated by CFD analysis, respectively. The $|\overline{v_p}|$ was averaged by the values of the solid/liquid relative velocity at each segment as shown in Fig. 15. The averaged $|\overline{v_p}|$ of each segment was substituted into Eq. (20) and k_1 was calculated from Eq. (18). The k_1 values of 5-segments were averaged once again at each powder blowing condition.

Figure 16 shows the relationship between solid/liquid mass transfer coefficient or interfacial area and pearlite feed rate. The solid/liquid interfacial area, a_1 , in Fig. 16(b) was obtained by substituting the calculated mass transfer coefficient, k_1 , in Fig. 16(a) into the mass transfer capacity coefficient, k_1a_1/V , as shown in Fig. 14. The k_1 value increased with the increase in pearlite feed rate, F_{Pl} , and Q_{TB} , and the decrease in LH . The effect of Q_{TB} and LH on k_1 is due to hard blowing. On the other hand, as seen in Fig. 16(b), the

a_1 value increased with the increasing F_{PI} at low F_{PI} and it is suppressed at $F_{PI} > 57.6$ g/min. The dependency of Q_{TB} and LH on a_1 was not clear.

Fig. 16. Relationship between solid/liquid mass transfer coefficient or interfacial area and pearlite feed rate.

Figure 17 shows the effect of penetration depth, L_p , on solid/liquid mass transfer properties such as (a) $k_1 a_1 / V$, (b) k_1 and (c) a_1 . The $k_1 a_1 / V$, k_1 and a_1 values increased with the increasing L_p when Q_{TB} and LH are fixed. As for the constant L_p , $k_1 a_1 / V$ and k_1 increased with the increase in Q_{TB} under the constant LH , although the effect of LH was not clear at the same Q_{TB} . As the larger Q_{TB} leads to the faster particle velocity as shown in Fig. 3, that is, the larger $|v_p|$, k_1 enhances with the increase in Q_{TB} . On the other hand, a_1 , which indicated a little bit spread of values as shown in Fig. 17(c), was summarized as a function of L_p due to the independency of Q_{TB} and LH at the constant L_p .

3.2.4. Particle Injection

The mass transfer rate for the particle injection was measured under the same condition as the penetration depth in Fig. 11. The relationship between $k_1 a_1 / V$ and pearlite feed rate is shown in Fig. 18. The $k_1 a_1 / V$ increased with the

Fig. 18. Relationship between solid/liquid mass transfer capacity coefficient and pearlite feed rate for particle injection.

Fig. 17. Relationship between solid/liquid mass transfer properties and penetration depth.

increasing Q_{TI} and ID . However, the increase in $k_1 a_1/V$ was small, although the pearlite feed rate became the 4-times large value. It is due to the crowded particles at the particle invasion spot.

4. Conclusions

The particle penetration depth and solid/liquid mass transfer rate of particle blowing were investigated by cold model experiments, and the CFD calculation of penetration depth by a combination of VOF and DEM model was carried out and compared with the experimental results.

(1) Both penetration depth and solid/liquid mass transfer rate increased with the increase in particle feed rate and top blowing gas flow rate, and the decrease in lance height and particle diameter.

(2) The calculated particle penetration depth was in good agreement with the experimental value.

(3) The following non-dimensional equation of particle penetration depth was obtained:

$$Re_P = 187 Fr^{0.673} We^{0.199} \left(\frac{\rho_l - \rho_p}{\rho_l} \right)^{0.447}$$

where, Re_P : particle Reynolds number, Fr : Froude number, We : Weber number, ρ_l and ρ_p : liquid and particle density (kg/m^3), respectively.

(4) The solid/liquid mass transfer coefficient calculated by the CFD simulation and Froessling equation increased with the increase in top blowing gas flow rate, particle feed rate and penetration depth.

(5) The solid/liquid interfacial area was expressed by a function of penetration depth.

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