Dispersion Characteristics of Laterally Injected Fluid into Main Stream in Packed Bed

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(Received on October 31, 2014; accepted on December 25, 2014)

For the reduction of the carbon dioxide emission from the steelmaking industries, various approaches to design the blast furnace operation with the injection of the reducing gas to the stack part have been made. To realize this technology, the flow behavior of the injected gas has to be quantitatively understood. This study focused to clarify the mechanism to determine the flow path of the injected gas, and the flow behavior of the stream which is laterally injected to the main stream in the packed bed was discussed through theoretical consideration, experiments and numerical flow simulation. The injected stream flows along the wall of injection side without penetrating the main stream. The dispersion degree coincides with the flow rate ratio of injected stream to total flow under the condition with uniform packing structure and fluid properties. The dispersion degree in the region enough downstream from the injection is independent of the injection velocity and direction. The dispersion degree can be controlled in some extent by controlling the difference in the fluid properties between the main and the injected streams and the distribution of the packing structure.

KEY WORDS: blast furnace; packed bed; injection; stack; dispersion; flow pattern.

1. Introduction

The gas injection from the stack part of blast furnace has been studied as one of the approaching methods to decrease the reducing agent rate by enhancing the indirect reduction,1–5) to improve heating of burden materials,6–8) and so on. With recent arise of social pressure to reduce carbon dioxide emission from steelmaking industry, various projects to develop blast furnace operations with the reducing gas injection to the stack part have been organized in Japan,9–12) Europe,5,13–16) and the other areas. Additionally the blast furnace operations under the conditions with the stack gas injection combined with low temperature operation or charging of carbon composite agglomerates were numerically analyzed.17–19)

For the enhancement of the indirect reduction of iron ores by injecting reducing gas, the contact degree of the injected gas with the iron ores should be quantitatively understood, and thus the trajectory of the injected gas in the furnace should be known. Nishio and Miyashita20) performed cold model experiments on the flow characteristics of the injected gas to the stack part using 2- and 3-dimensional cold models. They reported that the injected gas flows along the wall of injection side, and the ratio of the dispersion area of this injected gas to total cross sectional area of the bed was same as the ratio of the injected gas flow rate to the total gas flow rate. With these findings, they also discussed the effects of the gas mixing in the bed and the distribution of packing structure on the dispersion characteristics of injected flow. The mechanism by which the dispersion area is determined by the flow rate ratio has yet to be clarified. Thus the dispersion of the injected flow has been repeatedly discussed experimentally and numerically to date.14,21–25)

This study tries to clarify the mechanism of spreading behavior of the laterally injected gas flow into the main stream in packed bed based on theory of the fluid dynamics. Then the mechanism is validated through the experiments and numerical flow simulation. And finally the effects of injection conditions, uneven packing structure and fluid properties on the dispersion behavior are discussed.

2. Theory

This study deals with the dispersion behavior of the laterally injected fluid into the mainstream in packed bed. Dispersion degree is the extent to which the injected fluid reaches from the injection nozzle, and is defined as the area ratio of the injected flow to the bed in cross section. In this section, the mechanism to determine the dispersion degree
2.1. System and Assumptions

The packed bed discussed in this study has the longitudinally fixed cross section. The main stream flows unidirectionally in the packed bed. A fluid is laterally injected into the main stream from a nozzle settled on a side wall. The laterally injected fluid is the same phase as the main stream. In the actual packed bed, the voidage in the vicinity to the wall becomes higher than that in the middle part because the particles contact to the flat wall. This phenomenon is so called wall effect. The wall effect appears in the region within a few packed particle diameters from the wall, and this region is enough small compared to the whole packed bed volume. Thus it is assumed that no wall effect exist. This study assumes that the packing structures of the bed, namely voidage and packed particle diameter, are uniform and isotropic. It is also assumed that well-developed flow is formed in the region enough downstream from the injection nozzle. Here, the well-developed flow is defined as a unidirectional flow having constant velocity in longitudinal direction and no lateral motion. This study assumes that no diffusive mixing occurs in the bed. Additionally physical properties of the fluids, namely the density and the viscosity, are assumed constant.

2.2. Flow Path of Injected Stream

Flows of viscous fluid can be described by the continuity equation and the equation of motion. For the blast furnace condition, these equations take into account the voidage and flow resistance.

Continuity equation

\[ \frac{d}{dt}(\rho u) + \nabla \cdot (\rho u u) = 0 \] .......................... (1)

Equation of motion

\[ \frac{d}{dt}(\rho u u) + \nabla \cdot (\rho u u u) = -\nabla p + \nabla \cdot \tau + \rho g \] .......................... (2)

where, \( p, \rho, u, t, \rho, \rho, \rho \) and \( \tau \) are gravitational acceleration [m s\(^{-2}\)], pressure [Pa], velocity [m s\(^{-1}\)], time [s], voidage [–], density [kg m\(^{-3}\)] and stress tensor [Pa], respectively. The fourth term of the right side of the equation of motion, \( \tau \), is the flow resistance of packed bed [N m\(^{-3}\)], and the Ergun’s equation\(^{9}\) is widely used for the flow analysis in the blast furnace.

\[ \tau = \frac{150 (1-\varepsilon)^2 \mu}{\varepsilon^2 d_p^2} + 1.75 \frac{(1-\varepsilon)^2 \rho |\mu|}{\varepsilon \phi_\rho} \] .......................... (3)

where, \( d_p, \phi \) and \( \mu \) are particle diameter [m], shape factor [–] and viscosity [Pa s], respectively. Generally for the packed bed flow, inertial term, viscous term and buoyancy are negligibly small compared to the flow resistance term. By omitting these terms, the equation of motion under steady state can be expressed as:

\[ \nabla p = -C_0 \vec{u} \] .......................... (4)

In this equation, the flow resistance is rewritten as the product of the gas velocity and apparent drag coefficient \( C_0 \) [kg m\(^{-3}\) s\(^{-1}\)] which is expressed by the inside terms in brackets of Eq. (3). The flow expressed by this equation is potential flow in which the fluid motion is determined by the gradient of pressure.

Figure 1 schematically shows the variations of pressure and flow fields near wall region caused by the lateral injection into the main stream. Without the injection, the fluid flow is unidirectional and the pressure gradient is uniform. Thus the isobars are parallel and their spatial intervals are identical as shown in Fig. 1(a). Figure 1(b) schematically shows the distributions of pressure and flow with the injection. In this condition, fairly weak fluid flow is injected from the nozzle indicated by the cross mark and perpendicularly to the paper face. The pressure in the vicinity of the nozzle increases due to the fluid injection, and the pressure gradient in the region upstream of the nozzle decreases. Consequently the isobars in this region project toward the nozzle. Contrarily the pressure gradient in the downstream side of the nozzle become larger and the isobars project toward the downstream side. The fluids tend to flow perpendicularly to the isobars. Therefore, the main stream flows avoiding the nozzle. The main stream splits to the both sides of the nozzle and flows toward downstream. The injected flow disperses as flowing to downstream between the split main streams. Once the streams reach to the region with parallel isobars, no more dispersion occurs. Figure 1(c) shows the flow field with strong gas flow injection. The strong fluid injection raises the pressure in front of the nozzle, and the closed circle-wise isobar appears. The pressure distributions in both up- and downstream regions of the nozzle show the similar trend as the weak injection case. A part of the injected fluid flows toward upstream as well as downstream, and disperses radially. The fluid that flows toward downstream shows the same behavior as the weak injection case. The fluid that flows toward upstream reaches the region with the local minimum pressure, then turns toward downstream. Even in this case, the flow path of the injected fluid expands only till it reaches the region with the parallel isobars. No expansion of the flow path occurs in more downstream region.

The flow pattern in the direction of injection can be explained as follows. It is assumed that the injected gas penetrates the main stream and flows into the inside of the packed bed. In the upstream region of this penetration, the pressure increases and the main stream splits to avoid the injected flow. When the penetrating flow forms, the feeding of injected fluid to the near wall region of downstream of the nozzle vanishes. Thus the split main streams unite again to feed the fluid to the downstream of penetrating flow. Figure 2 shows a pressure distribution near wall to form this flow pattern. The pressure distribution in which the
isobars project to the upstream in the downstream region of the nozzle is required. In other words, the pressure in the downstream region of the nozzle becomes lower. In the potential flow scheme, the fluid injection simply raises the pressure as the velocity potential, and no pressure lowering should occur. Therefore, the laterally injected fluid should flow along the wall without penetrating the main stream as shown in Fig. 3(a). With low velocity injection, all injected fluid flow toward downstream as soon as it is introduced into the packed bed. Increase in the injection velocity raises the pressure increase in front of the nozzle. When this pressure rise is enough high to form the closed isobar, a part of the injected fluid once flows toward upstream, then it turns to downstream as shown in Fig. 3(b). Even in this case the injected fluid flows along the wall. Additionally, under the assumption of the isotropic packed structure, the velocity potential, namely the pressure, is also isotropic. Therefore, the flow patterns shown in Figs. 3(a) and 3(b) are common in any cross sections in longitudinal direction. Thus the dispersion of the injected fluid from the nozzle is constant, and the flow path shape perpendicular to the main stream is semicircle attaching to the wall as shown in Fig. 3(c).

2.3. Dispersion Degree of Injected Fluid

This section discusses the dispersion degree of laterally injected stream into the packed bed. The discussion in the previous section showed that the injected fluid flowed along the wall of injected side without detaching from the wall. Thus in 2-dimension, the dispersion of the injected flow corresponds to the width which the injected fluid occupies as shown in Fig. 4. The relation between the volumetric flow rate (V [m³/s]) and the velocity (u [m/s]) of the fluids can be described as

\[ V_m = \varepsilon A_m u_m \] ................................ (5)

\[ V_i = \varepsilon A_i u_i \] ................................ (6)

where, \( A \) is cross sectional area of the stream [m²], and subscripts “i” and “m” stand for injected and main streams, respectively. In case that the main stream and injected fluid have same physical properties, relationship between the velocity and the pressure gradient is common for both streams. Thus in the well-developed flow region, the velocities of the main stream and the injected fluid are the same (\( u_m = u_i \)). Under the condition of the uniform packed bed, the voidage is common between two streams. Therefore, the following relations can be obtained.

\[ \frac{A_i}{A_m} = \frac{V_i}{V_m} \] or \[ \frac{A_i}{A_m + A_i} = \frac{V_i}{V_m + V_i} \] ........................ (7)

These equations suggest that the cross sectional area ratio of the injected stream to the bed corresponds to the ratio of the injected flow rate to the total flow rate. This relationship depends only on the ratio of the volumetric flow rate, thus it is independent of the injection conditions like velocity, direction, and so on, and can be applied to not only 2-dimensional but also 3-dimensional system. In 2-dimensional system, the dispersion depth corresponds to the width of the injected stream. For 3-dimensional system, the dispersion depth can be defined as the radius of the semicircular flow region. That is to say, above discussion elucidates the mechanism of the flow behavior obtained experimentally by Nishio and Miyashita.20)

2.4. Effects of Fluid Properties and Packing Structure on Fluid Dispersion

The discussion in the previous section was made under the condition that the physical properties of two fluids were identical and the packing structure was uniform. In this section, the effects of the fluid properties and the packing structure on the dispersion of the injected stream. The relation between the velocity and the pressure gradient depends on the fluid properties. Concretely the pressure gradient increases with the increase in the viscosity and the density under the condition with constant velocity and uniform packing structure. Contrarily, under the constant pressure gradient condition, the fluid velocity decreases with increase in the viscosity and the density. From the relationship expressed by Eq. (7), the decrease in the velocity increases the cross sectional area of the stream.

The assumption of well-developed flow is also valid under the condition that the properties of two fluids are different. Figure 5 shows the effect of the fluid properties on the dispersion of the stream. In this figure, both main...
and injected streams are introduced from the bottom of the packed bed at the same velocity, and two streams equally occupy the bed at the bottom. When the fluid properties are common between two streams, the occupied areas are unchanged. With decrease in the viscosity and/or the density of the injected fluid, the friction force decreases. It causes the increase in the velocity of the injected stream and the dispersion of the injected stream decreases. Contrarily the higher viscosity and/or density increase the dispersion of the injected stream.

The difference in the friction forces can be also generated by the difference in the packing structure of the bed. The distribution of packing structure in perpendicular direction to the main stream direction generates the difference in the friction force between two fluids. With the packing structure in which the friction force is higher in the injection side, the velocity of the injected stream decreases and the dispersion increases. Therefore, the smaller voidage and the particle diameter in the injection side makes the dispersion degree larger.

3. Experiments and Numerical Analysis

In the previous section, the flow behavior of the laterally injected stream to the main stream in the packed bed was discussed theoretically. In this section this flow characteristics of the injected stream is confirmed through the experiments and the numerical flow analysis.

3.1. Experimental Apparatus and Procedures

Schematic diagram of the experimental apparatus to measure the dispersion degree of the laterally injected stream to the main stream in the packed bed is shown in Fig. 6, and the details of the packed bed is shown in Fig. 7. The packed bed has thin rectangular parallelepiped shape to make flat 2-dimensional flow with in it. The dimensions of the packed bed are 100 mm wide, 300 mm high and 20 mm deep. The main stream is introduced from the bottom of the bed. A slot nozzle of 10 mm width over the whole depth of the bed for the inlet of the injected flow is settled on a side of the packed bed at height of 100 mm. The vessel of the packed bed is made of Perspex board, and it allows to observe the inside of the vessel. The main stream and the injected stream are fed from their individual reservoirs at constant flow rates. The top part of the packed bed is divided by thin plates into 10 sections to sample the fluid that flows out from the bed.

The dispersion degree of the injected stream was measured by the following procedures. The vessel was filled by the particle at certain voidage. The main stream was introduced at certain flow rate from the bottom and then the injected stream was introduced from the side slot nozzle. The injected stream was dyed as red or salt (NaCl) was dissolved into the injected stream. After the steady state was attained, the fluid that flows out from the top of the bed was sampled from each section. The dispersion degree was determined by the spectrometry or electric conductivity measurement.

In this experiments, glass beads of 3.0 mm in diameter was used as the packed particles, and the voidage of the bed was set at 0.32 [–]. The fluid of the main stream is water. Two kinds of fluids were used as the injected stream. One is...
water and the other is glycerol aqueous solution of 60 wt-%. As mentioned above, the injected stream is dyed as red or salt is added. For the dyed fluid, the absorbance at the 500 nm was measured, and the electric conductivity was measured for the salt water. The concentrations of the red-dye and the salinity of the samples were determined by the preliminarily made calibration curves. Preliminary experiments using the dyed water and the salt water showed no significant difference in the measured dispersion degree. The flow rate of the main stream was set at $3.33 \times 10^{-5}$ or $5.00 \times 10^{-5}$ m$^3$ s$^{-1}$, and the injected stream flow rate was varied in the range from $8.33 \times 10^{-6}$ to $1.67 \times 10^{-5}$ m$^3$ s$^{-1}$.

As mentioned above, the macroscopic flow in the packed bed can be described as the potential flow. The Ergun’s equation (Eq. (3)) that estimates the flow resistance of packed bed consists of two terms. First term is of viscous resistance and is linearly proportional to the velocity. Second term is of turbulent resistance and is proportional to the square of the velocity. The former and the latter are dominant in laminar and turbulent flow conditions, respectively. This means that the fluid velocity in the packed bed is proportional to power from 0.5 to 1.0 of the pressure depending on the flow condition. Thus the macroscopic flow pattern of the fluids in the packed bed is governed by the ratio of first term to second term of the Ergun’s equation, not by the particle Reynolds number. This term ratio of this experimental condition is about 1.0 [-], while the one of the average flow condition in the blast furnace is about 20 [-]. The effect of this difference in the term ratio was preliminarily examined by the numerical flow simulation. The results showed that the effect appears only in the vicinity of the lateral inlet nozzle, and no effect is observed on the dispersion degree or the salinity of the samples were determined by the preliminary made calibration curves. The dispersion degree of the injected stream was determined by the following method. The concentration at the horizontal axis indicates the distance from the wall of the injection side to the center of each sampling section. The concentration in the vertical axis is defined as the relative concentration to the salinity of the injection fluid. In the region within the certain distance from the wall of the injection side, the concentration is almost unity, thus only injected fluid flows in this region. With increase in the distance from this region, the salinity abruptly decreases to zero. It means that only main stream flows in the region farther than this declining region. This trend is common for all conditions. It is obvious the dispersion degree of the injected stream increases with its flow rate. Its boundary, however, is unclear because the concentration changes within certain width. This is due to the diffusive mixing. Therefore, the dispersion degree of the laterally injected stream in the blast furnace condition can be discussed based on the small cold model experiments using water.

3.2. Numerical Flow Analysis

For more detailed discussion on the dispersion behavior of the laterally injected stream to the main stream under more various flow and packing conditions, the numerical flow analyses were performed. The fundamental equations of the analysis are the continuity equation and the equation of motion (Eqs. (1) and (2), respectively), and the flow resistance in the packed bed was evaluated by the Ergun’s equation (Eq. (3)). The fundamental equations in Cartesian coordinate system were discretized by using the control volume method. The SIMPLER$^{26}$ was applied to couple the fields of velocity and pressure.

In the flow analysis, vertical parallelepiped calculation domain is used. Main stream is uniformly introduced from the bottom at constant velocity. The injection nozzle is set on the center of one of the side faces. From this nozzle, the fluid is laterally injected at constant velocity. On all side faces but the injection nozzle part, slip condition is applied.

3.3. Results and Discussion

3.3.1. Experimental Results

The salinity distribution at the top of the packed bed is shown in Fig. 8. The flow rate of the main stream is $3.33 \times 10^{-5}$ m$^3$ s$^{-1}$ (superficial velocity: 0.0166 m s$^{-1}$). The salinity distributions under four conditions are plotted in the figure, namely three flow rates ($8.33 \times 10^{-6}$, $1.25 \times 10^{-5}$ and $1.66 \times 10^{-5}$ m$^3$ s$^{-1}$) for the salt water, and $1.25 \times 10^{-5}$ m$^3$ s$^{-1}$ for the glycerol aqueous solution. The distance in the horizontal axis indicates the distance from the wall of the injection side to the center of each sampling section. The concentration in the vertical axis is defined as the relative concentration to the salinity of the injection fluid. In the region within the certain distance from the wall of the injection side, the concentration is almost unity, thus only injected fluid flows in this region. With increase in the distance from this region, the salinity abruptly decreases to zero. It means that only main stream flows in the region farther than this declining region. This trend is common for all conditions. It is obvious the dispersion degree of the injected stream increases with its flow rate. Its boundary, however, is unclear because the concentration changes within certain width. This is due to the diffusive mixing. Therefore, the dispersion degree of the injected stream was determined by the following method. The salinity curve is first integrated from both sides as the salinity decrease from the injected stream side and the salinity increase from the main stream side. It is assumed that the diffusive mixing in this experiment occurs in the form of counter diffusion between salt water and water. With this assumption, the decrease in the salinity in the injected stream and the increase in the salinity in the mainstream side occurs symmetrically with respect to
the boundary between two streams. Thus the boundary, in other word, dispersion degree, is given by the location at which these two integral values are the same. The dispersion degree of the injected stream obtained by this procedure is specified by the arrow in the figure. The dispersion degree increases with the increase in the flow rate of the injected stream. The dispersion degree of the glycerol aqueous solution is larger than that of salt water at the same flow rate. In Fig. 9, the dispersion degree is plotted against the flow rate ratio of the injected stream. The dispersion degree in this figure is normalized by the bed width. For salt water, dispersion degrees for two flow rates of injected stream, namely $3.33 \times 10^{-5}$ and $5.00 \times 10^{-5}$ m$^3$ s$^{-1}$ are shown in the figure. Regardless of the main stream flow rate, the dispersion degree of the salt water coincides with the flow rate ratio. This validates the mechanism determining the dispersion degree of laterally injected stream explained in the previous section. The dispersion degree of the glycerol aqueous solution is larger than one of the salt water at the same flow rate. The density and the viscosity of the glycerol aqueous solution are 15.5 mPa s and 1 160 kg m$^{-3}$, respectively, and both are larger than those of water (1.23 mPa s and 1 000 kg m$^{-3}$). With these properties the pressure gradient of the glycerol aqueous solution is larger when the velocity is the same. Consequently the velocity of the glycerol aqueous solution becomes lower than that of main stream water in the well-developed flow in the downstream region, and the dispersion degree increases.

3.3.2. Effect of Injection Flow Rate

In the following sections, the dispersion degree of the stream laterally injected to the main stream is discussed in detail through the numerical flow analyses. In the analyses, two conditions were examined. One is of laminar condition and the other is turbulent condition. These conditions were set taking into account the flow conditions of the cold model experiments in the previous section and the flow condition in blast furnace. The flow analyses were performed in 2- and 3-dimensional frameworks, the respective common conditions were summarized in Table 1.

Two-dimensional analyses were performed for both cold model and blast furnace conditions. In these conditions, the ratio of the bed height to the bed width is 4.0 [–]. Both of these calculation domains were divided into $20 \times 80$ grids. Thus square grids of 0.005 and 0.05 m were used for the cold model and the blast furnace conditions, respectively. The injection nozzle is set at the height of bed width from the bottom, and the nozzle area (width) is a tenth of the bottom. The main stream inflow velocities are constant at the values shown in Table 1. The flow rate ratio of the injected stream is varied from 10 to 90% (1/10 to 9/10) of total flow rate. The properties of the injected stream are same as ones of the main stream. The dispersion boundaries of the injected flow at various flow rate ratios are shown in Fig. 10. The dispersion boundary shown in this figure is defined as the stream line of which origin locates the upstream edge of the injection nozzle. Under the assum-

![Fig. 10. Calculated variation of dispersion boundary with flow rate ratio.](image-url)
tion of no diffusive mixing, this stream line coincides with the boundary between the injected and main streams. Thus the distance from the wall of injection nozzle to this stream line at the packed bed exit indicates the dispersion degree. The boundaries shown in this figure are drawn from 10 to 90% with interval of 10% of flow rate ratio. The boundary moves from injection side to the other side with increase in the flow rate ratio. Under the conditions of 10% and 20%, the injected stream flows toward downstream immediately after the injection. Under the larger flow rate ratio conditions, a part of the injected stream flows toward upstream because the pressure increase in the vicinity of the nozzle becomes significant. This backward stream flows along the injection wall and then turns it direction to the main stream. Thus the stream line of dispersion boundary leaves from the wall in the upstream region of the nozzle. Finally the injected stream flows parallel to the main stream toward the exit. This overall flow pattern is common between the cold model and the blast furnace conditions, although these conditions show slight difference in the dispersion boundary in the vicinity to the injection nozzle due to the difference in the formation of high pressure zone. The dispersion degrees at the top of the packed beds are magnified in the right side of the figure. The dispersion degree agrees to the flow rate ratio, and there is no difference between the cold model and the blast furnace conditions. This result validates the theoretical explanation that the dispersion degree is independent of the packing condition and kind of the fluid, and determined only by the flow rate ratio of the injected stream under the condition with no diffusive mixing.

3.3.3. Effect of Injection Condition

Figure 11 shows the effect of the injection velocity on the shape of the dispersion boundary under blast furnace condition. The flow rate ratio of the injected stream is constant at 25%, and the inflow velocity is adjusted by the width of the nozzle. The widths of the nozzle are from 0.1 to 0.5 m with 0.2 m interval, and the corresponding injection velocities are 2.5 to 0.5 m s\(^{-1}\). The properties of the main and injected streams are identical. For the nozzle width of 0.1 and 0.3 m, a part of the injected fluid flow along the wall toward upstream. In these conditions the kinetic energy of injected stream is high enough to raise the pressure higher than that in the upstream region. This flow turns toward inside the main stream, and finally flows toward the downstream. Thus the dispersion boundary leaves the wall of injection side in the upstream region of the nozzle. With the wider nozzle, injection velocity decreases. With the nozzle of 0.5 m, the pressure along the injection wall monotonically decreases due to insignificant pressure rise. The injected stream flows immediately toward downstream direction. Thus the dispersion boundary is drawn from the upstream edge of the nozzle toward the downstream. As explained here, the injection velocity changes the flow pattern in the vicinity of the nozzle. The dispersion degrees of these conditions, however, are identical in the downstream region farther than 0.5 m from the nozzle. Furthermore the dispersion degree is 0.25 m which coincides to the flow rate ratio. This suggests that the dispersion degree in the well-developed region is independent of the injection velocity under the same flow rate conditions.
Figures 12 and 13 show the results of the 3-dimensional flow analysis under the blast furnace condition. Figure 12 shows the 3-dimensional shapes of the dispersion boundary of the injected stream. The horizontal cross section of the calculation domain is a square having the side of 1.0 m, and the flow rate ratio of injected stream is set at 25%. Two injection conditions were examined, namely the square nozzles of 0.1 and 0.3 m of their sides. The corresponding injection velocities are 25.0 and 2.78 m s⁻¹, respectively. The centers of the nozzles are set at the height of 1.0 m from the bottom. The physical properties of the injected stream are same as ones of main stream. The dispersion boundaries have spherical shape in the region lower than the nozzle, and semicylinder in the region higher than the nozzle. The cross sectional areas of both semicylinders are almost 25% of the bed cross section. Comparing the dispersion boundary shapes in two conditions in details, the bottom shape for larger nozzle is slightly more roundish. About the semicylinder part, the width is little bit wider and the depth is shallower under the larger nozzle condition. This is because the injected stream from the larger nozzle is easier to spread laterally due to wider width of the nozzle. In other words, this small difference is brought by the difference in the nozzle shape, not by the injection velocity. Therefore, it is considered that the dispersion boundary shape is independent of the injection velocity even in 3-dimensional flow. Contrarily to the boundary shape, the flow characteristics near the nozzle show large difference. Figure 13 shows the dispersion boundary, pressure distribution and velocity vector along the wall of injection side. In the high velocity (small nozzle) condition, a steep pressure peak appears just in front of the nozzle. With this pressure distribution, the injected stream scatters in all directions from the nozzle with high velocity. The injected stream toward upstream (downward) reaches to farther area from the nozzle. In the low velocity condition, the pressure increase in front of the nozzle is insignificant, and only weak upstream flow forms. Thus the injected stream is swept by the main stream immediately after leaving the nozzle. In both conditions, the velocity vectors are drawn almost vertically upward and the dispersion boundary on the wall is straight and vertical in the upper part of the bed. This means that no wraparound flow of the main stream in the downstream of the nozzle occurs. Furthermore these pressure and velocity vector distributions are almost identical in any vertical cross sections including the center of the nozzle.

Above mentioned flow characteristics suggest that the dispersion region of the injected stream spreads radially and forms semicircular cross section in uniform and isotropic packed bed. The area of this semicircle is determined by the flow rate ratio of the injected stream and independent of the injection velocity. In contrast, the flow pattern in the vicinity of the injection nozzle strongly depends on the injection velocity.

The flow patterns of injected stream at three different inflow directions are shown in Fig. 14. The flow analyses were performed under the blast furnace condition in 2-dimensional framework. The inflow directions are perpendicular to the main stream and slanted 30 degrees to up- and downstream direction. The flow rate ratio of the injected stream is 40% of total flow rate. In this figure, the velocity vector, the pressure distribution and the dispersion boundary are depicted simultaneously. For three conditions the isobars of the same values are drawn, and the pressure interval is 100 Pa. Although the directions of the velocity vectors at the nozzle are different one another, overall flow patterns are almost identical. Slight difference can be observed in the vicinity of the nozzle. Concretely, as the injection direction toward the upstream, the gradient of the isobar of 2.9 kPa becomes steeper in the figure, and the area of the region of which pressure is higher than 3.0 kPa at the nozzle gets larger. With this change in the pressure distribution, the flow toward upstream from the nozzle get stronger, and the dispersion boundary shifts toward upstream. This variation, however, is minor. The flow field in downstream region from the nozzle shows little change, and the dispersion degree is unaffected by the injection direction.

3.3.4. Effect of Fluid Properties

The effects of the fluid viscosity and density on the dispersion degree are examined through 2-dimensional flow analysis. The analyses are performed for both cold model and blast furnace conditions. In both conditions, the flow rate ratio of the injected stream is set at 40%, and the area of the injection nozzle is 20% of the packed bed cross section. Halved or doubled viscosity and density are individually examined. The dispersion boundaries under these conditions are shown in Fig. 15, and the dispersion degree at the top of the bed is summarized in Table 2. For both cold model and blast furnace conditions, increases in the viscosity and the density widen the dispersion degree. The effect of the viscosity, however, is little in the blast furnace condition. This trend can be explained based on the Ergun’s equation (Eq. (3)). Under the cold model condition, the averaged flow scheme is laminar, and the magnitudes of first and second terms of the Ergun’s equation are comparable. Contrarily the second term including density is about 70 times larger than the first term including viscosity under the blast furnace condition. Therefore, the dispersion degree under the cold model condition depends on both viscosity and density of the injected stream, while one under blast furnace condition is almost independent of the viscosity.

The variation of the flow field near exit region with the density under the blast furnace condition is shown in Fig.
Table 2. Dispersion degree.

| Cold model (100 mm) | Blast furnace (0.1 m) |
|---------------------|------------------------|
| Viscosity Density   | Viscosity Density      |
| ×0.5 36.8 mm 32.5 mm | 0.3995 m 0.300 m       |
| ×1.0 40.0 mm 40.0 mm | 0.4000 m 0.400 m       |
| ×2.0 45.5 mm 48.5 mm | 0.4015 m 0.501 m       |

Fig. 15. Effect of fluid properties on dispersion boundary.

The maximum and the minimum diameters are 50 and 20 mm, and ones of voidage are 0.50 and 0.36 [–]. Three distribution patterns are examined, namely, up diagonal, down diagonal and uniform at median value. For the analysis on the voidage distribution, the packed particle diameter is uniform at 35 mm, and the voidage was 0.43 [–] for the analysis on the diameter. The dispersion boundaries obtained under these conditions are shown in Fig. 17. The flow rate ratio is set at 40%, and the dispersion degree from the injection wall for uniform bed is 0.4 m. For up diagonal particle diameter distribution (larger at injection side), the dispersion degree decreases to 0.350 m, while one in down diagonal condition increases up to 0.456 m. Similarly, the dispersion degree for up diagonal voidage distribution becomes smaller (0.331 m), and one for down diagonal condition is larger (0.476 m). In both cases, the dispersion degree increases in the packing structure in which the flow resistance is higher in the injection side. This tendency agree well with the one suggested in the section 2.4.

4. Conclusions

In this study, the flow behavior of the stream which is laterally injected to the main stream in the packed bed was discussed through theoretical consideration, experiments and numerical flow simulation. The results obtained in this study can be summarized as follows.

(1) The injected stream flows along the wall of injection side without penetrating the main stream. The cross section of the injected stream is semicircle in 3-dimensional uniform packed bed.

(2) When the fluid properties are common between the main and the injected streams, the dispersion degree coincides with the flow rate ratio, and is independent of the injection velocity and direction.

(3) When two fluids have different properties, the
injection of the fluid of which properties increase the flow resistance increases the dispersion degree.

(4) When the packing structure distributes in perpendicular direction to the main stream, the distribution in which the flow resistance is higher in the injection side increases the dispersion degree.

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