1. Introduction

From a viewpoint of global environment, the decrement in CO$_2$ emission is a serious problem to be solved. A large amount of CO$_2$ is emitted from the steel production, where the blast furnace consumes the largest energy. Accordingly, it is very effective for the decrement in CO$_2$ to improve the energy efficiency in the blast furnace.\(^1\)

In Japan, in order to minimize the CO$_2$ emission, it is proposed to increase the amount of pulverized coal injection and, as a result, to decrease the coke amount. However, this operation may bring about the change in packed structure of the lower part of the blast furnace, which may cause abnormal behavior of liquid flow such as local flooding.

On the liquid flow in the lower part of the blast furnace, some papers have been reported. Matsuura \textit{et al.}\(^2\) and Ohno \textit{et al.}\(^3\) have used a network model and simulated the liquid flow behavior. Li \textit{et al.}\(^4,5\) have used the bed packed with different particles and measured the distribution of liquid flow rate. They have used a percolation model and calculated the liquid flow distribution. Usui \textit{et al.}\(^6\) have modeled the lower part of the blast furnace by a moving bed and measured the liquid flow distribution. Recently, Husslage\(^7\) has reviewed some papers and examined the liquid flow in the blast furnace.

In this study, the liquid flow behavior in the lower part of the blast furnace (cohesive and dripping zones) was focused. To model a void, several glass particles coated with PTFE (polytetrafluoroethylene) were packed in the column with a little larger diameter than that of particle. The effects of packed structure and liquid properties on the liquid flow behavior were examined. Different-size glass particles coated with PTFE were packed in the column, and the pressure loss and liquid holdup in the packed bed were measured. The liquid loading and flooding points were obtained from the change in pressure loss.

Both the gas velocities at loading and flooding points decreased with increasing volume fraction of small particle, with increasing liquid viscosity and with increasing liquid velocity. As the small particle fraction is higher, the total and static liquid holdups increase but the dynamic one decreases. These holdups were expressed by the experimental equations.

The liquid behavior in one void was modeled and analyzed. From the force balance on the liquid droplet at the flooding point the upward and downward forces were examined, and the variation in liquid flow behavior in the lower part of the blast furnace was estimated.

2. Experimental

2.1. Experimental Apparatus

Figure 1 shows the outline of the experimental apparatus. The column was made of transparent acrylic resin. The diameter and height were 22 and 600 mm, respectively. Six
glass particles coated with PTFE were packed in the column. The diameter was 20 mm and the contact angle was about 105 degree. A liquid nozzle with 4.5 mm in diameter was placed above the particle bed and a gas nozzle with 3.0 mm in diameter was fitted at the sidewall of the lower part of column. Pressure tap was installed at the gas inlet and connected to a manometer. Liquid was fed from a roller pump and the liquid level in the column was maintained to be constant (48 mm from the bottom) to cancel the effect of liquid fluctuation. Gas was fed at the point of 20 mm higher than the liquid level. The effective bed height was 58 mm.

2.2. Experimental Conditions
Glycerol aqueous solution and air were used as the liquid and gas phases. The liquid viscosity was prepared by changing the glycerol concentration. The physical properties of liquid with different concentrations are listed in Table 1. Table 2 shows the experimental conditions. The superficial velocities of liquid and gas based on the cross-sectional area of empty column were respectively changed in the ranges of 0.2–1.6 mm/s and 0–2.2 m/s, which were determined from the actual conditions in the blast furnace.\(^8\)

The packed structure was changed by means of the volume fraction of small glass particle coated with PTFE, whose diameter was 6 mm.

The liquid velocity was set at a given value and the gas velocity was changed. The flow pattern was observed and the pressure loss was measured. The liquid holdup was measured as follows; after the flow pattern became stable, the inlet and outlet of liquid were simultaneously shut. The dynamic liquid holdup was calculated from the increment in liquid level. After this the gas feed was stopped, and the remaining void was filled with liquid, from whose volume the static liquid holdup was estimated.

3. Results and Discussion
3.1. Gas Velocities at Loading and Flooding
3.1.1. Effect of Packed Structure on Gas Velocities at Loading and Flooding Points

Figure 2 shows the change in gas pressure loss with increasing gas velocity for different small particle fractions and liquid viscosities. The velocity is based on the cross-sectional area of empty column. The pressure loss gradually increases with increasing gas velocity. When the gas velocity is beyond a certain value, however, the increment drastically becomes larger. At the gas velocity, liquid loading starts to occur. Beyond this gas velocity, the pressure loss continues to increase largely. The highest gas velocity for each run shows the flooding point. At this gas velocity, the pressure loss begins to fluctuate too largely to be measured. Also the measurement with decreasing gas velocity from the gas velocity below the flooding point was performed. The pressure loss showed the similar tendency, and the loading point was the same as that in the case of increasing gas velocity for each run. For the same liquid viscosity, the gas velocities at loading and flooding points become lower as the fraction of small particle is larger. This reason is considered as follows; as the volume fraction of small particle is larger, the void in which gas flows becomes smaller. As a result, the true velocity of gas is higher, and loading and flooding are easier to occur. The measured pressure loss was much higher than that calculated from Ergun’s equation. This is considered because the liquid behavior in a large void is abnormal.

3.1.2. Effects of Liquid Properties on Loading and Flooding Velocities

Figure 3 shows the effect of liquid viscosity on the gas velocities at loading and flooding points.

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**Table 1.** Physical properties of liquid used in this study.

<table>
<thead>
<tr>
<th>glycerol conc.</th>
<th>( \mu_l ) [mPa·s]</th>
<th>( \rho_l ) [kg/m³]</th>
<th>( \sigma_l ) [mN/m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1000</td>
<td>72</td>
</tr>
<tr>
<td>60</td>
<td>10</td>
<td>1160</td>
<td>67</td>
</tr>
<tr>
<td>85</td>
<td>100</td>
<td>1220</td>
<td>65</td>
</tr>
<tr>
<td>93</td>
<td>300</td>
<td>1240</td>
<td>64</td>
</tr>
<tr>
<td>95</td>
<td>500</td>
<td>1250</td>
<td>64</td>
</tr>
</tbody>
</table>

**Table 2.** Experimental conditions.

<table>
<thead>
<tr>
<th>( u_l ) [mm/s]</th>
<th>0.2 – 1.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u_G ) [m/s]</td>
<td>0 – 2.2</td>
</tr>
<tr>
<td>( X_s [-] )</td>
<td>0, 0.05, 0.10</td>
</tr>
</tbody>
</table>
Locivity was relatively low, the liquid flow pattern was varied with the liquid viscosity. While liquid flowed as a trickle flow in the case of lower viscosity (tap water), it flowed as a string flow in the case of higher viscosity (glycerol solution used). However, beyond the gas velocity at loading point, the flow pattern showed the similar behavior, which was a liquid-film flow. Both the gas velocities at loading and flooding points become lower as the liquid viscosity is higher. This is because the liquid holdup is higher.

Figure 4 shows the effect of liquid velocity on the gas velocities at loading and flooding points. The liquid viscosity is 300 mPa·s and no small particle is added. Both the gas velocities become lower as the liquid velocity is higher. This is because the dynamic liquid holdup becomes higher. As the liquid velocity increases, the difference in gas velocities between loading and flooding points becomes less. This is considered because flooding is easier to occur as the dynamic holdup increases. The similar tendency has been reported in the previous paper.8)

3.1.3. Comparison of Flooding Data between This Study and Previous Studies

Figure 5 is the Sherwood diagram made from the previous data.9) We plotted our data on this diagram. When the flooding factors for our data are calculated by using the specific area of particle (\( \frac{A_p}{H} \)), the values are lower than the data of previous studies. So, we recalculated our data by adding the wall area of column to the particle area. These data (\( \dot{\circ} \)) show a good agreement with previous data. From this, it is found that the wall effect should be taken into account for the large and heterogeneous void in packed column.

3.2. Liquid Holdup

Figure 6 shows the change in total, dynamic and static liquid holdups with increasing gas velocity for different small particle fractions and liquid properties. For all the cases, the dynamic holdup is almost constant, regardless of the change in gas velocity. The total and static holdups, on the other hand, are unchanged at the relatively low gas velocity, but they start to increase beyond a certain gas velocity. This gas velocity means the loading point, and agrees well with the one obtained from the change in pressure loss.

As the volume fraction of small particle increases, the dynamic holdup increases. This is because the void size becomes smaller and the resistance to liquid flow becomes larger. The static liquid holdup, on the other hand, shows the reverse tendency. This is considered because the volume of void in which liquid is held, is smaller. The values of holdups are much different from the equations of Fukutake and Rajakumar9) which are derived from the data in the uniformly packed bed. Also the effect of small particle fraction on the static holdup is quite different. These are considered to be due to the abnormal void which were formed by both the particle and column wall. As the liquid viscosity increases, both the dynamic and static liquid holdups increase.
The total liquid holdup is expressed by a sum of dynamic and static ones.

\[ h_t = h_d + h_s \] ...................................(1)

For the dynamic liquid holdup, we modified the equation of Fukutake and Rajakumar \(^8\) by taking into account the term of void fraction as follows;

\[ h_d = 0.15 \frac{Re^{0.6} Ga^{-0.4} \varepsilon^{-3.2}}{Re^{0.6} \varepsilon^{0.4}} \] .................(2)

where the particle diameter \(d_p\) is the mean diameter based on the surface area and volume of particle. We tried to correlate the static liquid holdup using the equations of Fukutake and Rajakumar \(^9\), \(^10\), \(^11\) but we obtained no agreement. So, in this study, we divided it into two parts (the static holdup below the loading point and the increment in static holdup beyond loading point) and expressed them by the experimental conditions;

\[ h_s = h_{s0} = 3.7 \mu_L^{0.08} \varepsilon^{4.8} (u_G - u_{GL}) \] ......................(3)

\[ h_s - h_{s0} = 0.082 \varepsilon^{0.5} \mu_L^{0.1} d_p^{0.35} \mu_L^{-0.9} (u_G - u_{GL}) (u_G > u_{GL}) \] ......................(4)

In above equations, the void fraction is found to have a large effect on the liquid holdups. This effect should be examined in detail.

**Figure 7** shows the comparison of the total liquid holdup between measured data and results calculated from Eqs. (1)–(4). The calculated results reproduce the measured data within 25% of error.

### 3.3. Analysis of Liquid Flow Behavior in One Void

#### 3.3.1. Model of Liquid Flow in One Void

**Figure 8** shows the model of liquid flow in one void, which is used in analyzing the liquid flow. As described above, the flow pattern of liquid is different by the liquid viscosity and the gas velocity. However, for the simplification, the shape of liquid droplet was assumed to be a sphere whose diameter was calculated from the liquid holdup. Here, the static holdup below the loading gas velocity, \(h_{s0}\) was considered to have no influence on the liquid droplet. On the liquid droplet, the downward gravitational force and upward force work. The upward force, which is the resistance to liquid flow, consists of drag force, viscous force, buoyant force and so on.

#### 3.3.2. Upward and Downward Forces

The downward force is a gravitational force;

\[ F_d = V(h_t - h_{s0}) \rho_G g \] .................(5)

As described above, the upward force includes various forces. In this study, the upward force was assumed to be based on the kinetic energy of gas flow;

\[ F_u = \alpha A_L \rho_G v_G^2 \] .................(6)

The cross-sectional area of liquid, \(A_L\) is based on the diameter of liquid droplet, and \(v_G\) is the true velocity in the void;

\[ v_G = u_G/(1 - h_t) \] .................(7)

The coefficient \(\alpha\) in Eq. (6) was derived from the data at flooding point where the upward and downward forces are balanced. The coefficient is expressed by the true liquid holdup \((h_t - h_{s0})\) and the liquid viscosity as follows (see **Fig. 9**);
downward force in the upward force is plotted against the increasing void fraction from the standard condition. Both the upward and downward forces are calculated by decreasing the void fraction. As the standard conditions in the lower part of the blast furnace, the viscosity and velocity of liquid are set to be 300 mPa·s and 0.2 mm/s, and the gas velocities are between the loading and flooding points. These three gas velocities are 1.0, 1.5 and 2.0 m/s. These three gas velocities are changed to be 1.0, 1.5 and 2.0 m/s. These three gas velocities are changed to be 1.0, 1.5 and 2.0 m/s.

3.3. Contribution of Upward Force to Downward Force

To examine the contribution of upward force to the downward force, the upward force is plotted against the downward force in Fig. 10. The data at flooding point show the straight line with a slope of unity going through the origin. It is interesting that the data at loading point also ride on a straight line going through the origin.

Figure 11 shows the change in liquid flow behavior with decreasing void fraction. As the standard conditions in the lower part of the blast furnace, the viscosity and velocity of liquid are set to be 300 mPa·s and 0.2 mm/s, and the gas velocity is changed to be 1.0, 1.5 and 2.0 m/s. These three gas velocities are between the loading and flooding points. Both the upward and downward forces are calculated by decreasing the void fraction from the standard condition ($e = 0.38$). As the void fraction decreases, the force balance approaches to the flooding line. At the void fraction where the force balance crosses over the flooding line, the local liquid flooding is expected to occur. That is, the information on the local liquid flow in the blast furnace can be obtained from the force balance on the liquid flow.

4. Conclusion

In this work, a void in the lower part of blast furnace was simulated by using a small trickle bed and the liquid flow behavior was examined. The gas velocities at loading and flooding points were estimated from the change in pressure loss. Also the liquid holdups were measured and the force balance on the liquid flow was examined. The following facts were clarified:

1. The loading and flooding gas velocities decrease with increasing volume fraction of small particle, with increasing liquid viscosity and with increasing liquid velocity.
2. As the volume fraction of small particle is higher, the total and static holdups increase but the dynamic holdup decreases. The value and tendency of holdup are quite different from those in the uniformly packed bed.
3. By using the equations for liquid holdups, upward and downward forces, the force balance on the liquid flow in one void can be examined. From the force balance, the local behavior of liquid flow in the lower part of the blast furnace can be estimated.

![Plot of upward force against downward force.](image)

![Change in liquid flow behavior with decreasing void fraction.](image)

\[ \alpha = 0.016(h_1 - h_0)(\mu_G/\mu_w)^{0.1} \]

Nomenclature

\[ \alpha \] Cross-sectional area of liquid droplet (m²)
\[ \alpha_1 \] Specific surface area of particle (m⁻¹)
\[ d_1 \] Mean diameter of particle (m)
\[ F_d \] Downward force (N)
\[ F_u \] Upward force (N)
\[ g \] Gravitational acceleration (m/s²)
\[ Ga \] Galilei number (—)
\[ h_d \] Dynamic liquid holdup (—)
\[ h_s \] Static liquid holdup (—)
\[ h_0 \] Static liquid holdup below loading gas velocity (—)
\[ h_l \] Total liquid holdup (—)
\[ Re \] Reynolds number (—)
\[ u_0 \] Superficial gas velocity based on cross-sectional area of column (m/s)
\[ u_{G,F} \] Gas velocity at flooding point (m/s)
\[ u_{G,L} \] Gas velocity at loading point (m/s)
\[ u_{L,F} \] Superficial liquid velocity based on cross-sectional area of column (m/s)
\[ V \] Volume of packed bed (m³)
\[ v_g \] True gas velocity defined by Eq. (7) (m/s)
\[ \lambda \] Coefficient in Eq. (6) (—)
\[ \varepsilon \] Void fraction (—)
\[ \mu_L \] Viscosity of liquid (Pa·s)
\[ \mu_W \] Viscosity of water (Pa·s)
\[ \rho_g \] Density of gas (kg/m³)
\[ \rho_L \] Density of liquid (kg/m³)
\[ \sigma_l \] Surface tension of liquid (N/m)

REFERENCES

8) Y. Toyoda, A. Matsubara and Y. Bando: CAMP-ISIJ, 16 (2003), 788.