Correlation between Liquid/liquid and Gas/liquid Mass Transfers in a Top/Bottom Blowing Converter

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In this study, a calculation procedure of gas/liquid mass transfer capacity coefficients based on liquid/liquid ones was developed and cold model studies on benzoic acid transfer between water and liquid paraffin, and oxygen transfer among water, liquid paraffin and air was carried out under various top/bottom blowing rates and liquid/liquid volume ratios. The liquid/liquid mass transfer rate increased with the increase in a top blowing rate, but the increasing rate of a larger vessel diameter to the top blowing rate was lower than that of a smaller one. The gas/liquid mass transfer rate increased with the increase in both of top and bottom blowing rates, but the difference became reduced with the increase in the top blowing rate. The bottom blowing rate to minimize the sum of the top and bottom gas flow rates was almost constant for a given gas/liquid or liquid/liquid mass transfer rate. The liquid/liquid mass transfer rate increased and the gas/liquid one decreased with the increase in liquid paraffin volume ratio to water. There was a roughly positive correlation between the liquid/liquid and gas/liquid mass transfer rates throughout a wide range of top and bottom blowing rates, but the tendency was the opposite under the condition of the same paraffin volume and total blowing rate.

KEY WORDS: liquid/liquid mass transfer; gas/liquid mass transfer; top/bottom blowing converter.

1. Introduction

Both slag/metal and gas/metal reactions occur to remove impurities in steel melt in a converter. Cold model studies are conducted effectively to investigate mass transfer rates between different phases such as slag/metal and gas/metal, because a wide range of experimental condition can be set and effects of operation factors on mass transfer rate have been understood easily.

Many investigations on the slag/metal mass transfer rate have been carried out by using a variety of liquids to resemble the slag and metal. These are Hg - FeCl3 aq.,1) NaOH aq.- n-hexane,2) water - liquid paraffin,3–5) water - benzene,1) water - benzene and water - oil systems for bottom blowing, water - liquid paraffin and water - benzene systems for top blowing, and water - liquid paraffin and water - oil systems for top/bottom blowing. On the other hand, cold model studies on the gas/metal mass transfer rate are as follows: NaOH aq. - CO2, water - CO2, water - O2 systems for bottom blowing, NaOH aq. - CO2 systems for bottom blowing, and water - O2 systems for top blowing, NaOH aq. - CO2 and water - O2 systems for top blowing, and NaOH aq. - CO2 and water - O2 systems for top/bottom blowing. In the above studies, the effects of gas flow rate, bath depth, tuyere configuration etc. on the mass transfer rate between different phases have been examined, and in addition there have been a few studies on a contribution of stirring energy, which was supplied into a bath, to the mass transfer rate by making a comparison among bottom, top and top/bottom blowing.

However, there are few studies on a correlation between the liquid/liquid and gas/liquid mass transfer rates under the same vessel and operation conditions. As for the contribution of top or bottom blowing to accelerate the mass transfer rate between different phases, the liquid/liquid or gas/liquid mass transfer rate in top/bottom blowing might have a different tendency compared with top blowing or bottom blowing independently.

The present work was intended to understand the correlation between the liquid/liquid and gas/liquid mass transfer rates. After developing a calculation procedure of both liquid/liquid and gas/liquid mass transfer capacity coefficients, the mass transfer rate of benzoic acid between water and liquid paraffin, which simulated the slag/metal system, and the mass transfer rate of oxygen among water, liquid paraffin and air corresponding to the gas/metal system were examined under the same operational condition using converter-typed vessels.
2. Experiment

Figure 1 shows a schematic diagram of experimental arrangement. Ion-exchanged water was used as a continuous phase, whereas liquid paraffin as a dispersed phase. A schematic view of a lance tip is shown in Fig. 2. It has three straight type holes with $1.5 \times 10^{-3}$ m in diameter. Each gas injection angle to the lance central axis was fixed to 15 degree. Figure 3 shows a schematic diagram of bottom blowing nozzle arrangement. Five nozzles with $3.0 \times 10^{-3}$ m in diameter were set in a zigzag alignment. Vessel dimensions are shown in Table 1 where the symbols are defined in Fig. 1. Two kinds of vessel were used for the experiment.

Air through the top blowing lance and the bottom blowing nozzles was introduced to ion-exchanged water deaerated by nitrogen injection and oxygen-saturated liquid paraffin by air injection. A conductance meter and a dissolved oxygen meter (DO meter) were put into water to measure temporal changes in benzoic acid and oxygen concentrations, respectively.

The liquid/liquid mass transfer rate from liquid paraffin to water was measured by a temporal change in benzoic acid concentration in water. On the other hand, the gas/liquid mass transfer rate, which was evaluated without differentiating between contributions of top and bottom blowing, was obtained from a temporal change in oxygen concentration moved from injected air through the top blowing lance and bottom blowing nozzles and from liquid paraffin to water.

Experimental conditions of the top and bottom blowing are shown in Table 2. Gas flow rate from the top blowing lance was changed between 0 and $180 \times 10^{-3}$ m$^3$/min, gas injection rate through bottom blowing nozzles were varied between $30 \times 10^{-3}$ and $70 \times 10^{-3}$ m$^3$/min, although the lance height and the water volume were fixed to 0.200 m and $10.8 \times 10^{-3}$ m$^3$, respectively. The volume of liquid paraffin as the dispersed phase was varied to 0, $1.0 \times 10^{-3}$, $3.0 \times 10^{-3}$ and $5.0 \times 10^{-3}$ m$^3$. The temperature of ion-exchanged water and liquid paraffin were kept to $298 \pm 3$ K.

3. Results and Discussion

3.1. Calculation of Liquid/liquid and Gas/liquid Mass Transfer Rates

3.1.1. Liquid/liquid Mass Transfer Rate

Benzoic acid concentrations near the liquid/liquid interface and the overall driving force of mass transfer between liquid paraffin and water are shown in Fig. 4. The slope, $h_B^{\ast}$, of the equilibrium line is given by the ratio of $C_{B,w}^{\ast}$, which is benzoic acid concentration in water in equilibrium with that in liquid paraffin, to $C_{B,oil}$, which is benzoic acid concentration in liquid paraffin.

$$h_B^{\ast} = \frac{C_{B,w}^{\ast}}{C_{B,oil}}$$

By using the overall driving force, $(C_{B,w}^{\ast} - C_{B,w})$, and overall mass transfer capacity coefficient of benzoic acid between liquid paraffin and water, $K_{B,L-L}$, the mass transfer rate of benzoic acid from liquid paraffin to water is given by Eqs. (2) and (3).

$$\frac{dC_{B,w}}{dt} = K_{B,L-L} \left(C_{B,w}^{\ast} - C_{B,w}\right)$$

Table 2. Experimental conditions of top and bottom blowing.

| Condition                        | Value         |
|----------------------------------|---------------|
| Gas flow rate from top lance, $Q_T$ ($10^{-3}$ m$^3$/min) | 0–180         |
| Gas injection rate through bottom nozzles, $Q_B$ ($10^{-3}$ m$^3$/min) | 30–70         |
| Lance height, $L$ (m)            | 0.20          |
| Volume of water, $V_w$ ($10^{-3}$ m$^3$) | 10.8          |
| Volume of liquid paraffin, $V_{oil}$ ($10^{-3}$ m$^3$) | 0, 1.0, 3.0, 5.0 |
When both of the benzoic acid concentrations in liquid paraffin and in water are diluted sufficiently, the $h_B^*$ value becomes constant. According to the Wilke-Chang equation\(^{27}\) which enables to estimate diffusivities of benzoic acid in water and in oil, $D_{B,oil}/D_{B,water}$ was calculated to be about 3.2. Assuming that the mass transfer coefficient was proportional to square root of the diffusivity proposed by Higbie,\(^{27}\) $k_{B,water-L}/(k_{B,oil-L}/h_B)$ was calculated as follows:

$$k_{B,water-L}/(k_{B,oil-L}/h_B^*) = \left(3.2^{27}\right)(0.445) = 0.80 \ldots (4)$$

where $h_B^*$ is 0.445.\(^{26}\) It means that a rate-determining step in the mass transfer rate of this system is mixing diffusion of benzoic acid in water and oil phases.

Mass balance of benzoic acid can be expressed by,

$$C_{B, oil}V_{oil} + C_{B, water}V_{water} = \alpha \quad \text{................. (5)}$$

Substituting Eqs. (1) and (5) into (2) and eliminating $C_{B,water}$, Eqs. (6)–(8) are obtained from the initial condition of $C_{B,water}=0$:

$$m_1 - C_{B,water} = \exp(-m_1t) \quad \text{................. (6)}$$

$$m_1 = (K_{B,water-L}/a_{water})(h_B^*V_{water}/V_{oil} + 1) \quad \text{................. (7)}$$

$$m_2 = (h_B^*a_{oil}/V_{oil})/(h_B^*V_{water}/V_{oil} + 1) \quad \text{................. (8)}$$

$K_{B,water-L}$ can be obtained from a temporal change in $C_{B,water}$ and Eqs. (6)–(8).

### 3.1.2. Gas/liquid Mass Transfer Rate

**Figure 5** shows a schematic diagram of the oxygen transfer to liquid phases. Oxygen from air through the top blowing lance transfers to water (A) and liquid paraffin (C) and liquid paraffin to degassed water is given by the oxygen balance in water as follows,

$$\frac{dC_{O,water}}{dt} = K_{O,water-L}a_{water}(C_{O,water} - C_{O,water}^*) - C_{O,water}^* \quad \text{................. (9)}$$

where $C_{O,water}$, $C_{O,water}^*$ and $C_{O,water}^*$ are oxygen concentrations in water, in equilibrium with oxygen in air and in equilibrium with oxygen in liquid paraffin, respectively. The first and second terms of the right side in Eq. (9) indicate the oxygen transfer rates from air to water (A and B in Fig. 5) and that from liquid paraffin to water (D in Fig. 5), respectively. In this study, the oxygen concentration in liquid paraffin is assumed to be kept saturated due to the sufficient oxygen transfer from air through the top blowing lance to liquid paraffin (C in Fig. 5).

Integration of Eq. (9) under the initial condition of $C_{O,water} = C_{O,water,0}$ led to the following equations.

$$\frac{(P_1 - C_{O,water})}{(P_1 - C_{O,water,0})} = \exp(-P_1t) \quad \text{................. (10)}$$

$$P_1 = \left(K_{O,water-L}a_{water}C_{O,water}^* + K_{O,water-L}a_{water}C_{O,water}^*\right)/\left(K_{O,water-L}a_{water} + K_{O,water-L}a_{water}\right) \quad \text{................. (11)}$$

$K_{O,water-L}$ can be expressed by Eq. (13) as well as Eq. (3).

$$C_{O,water} = C_{O,water}^* \quad \text{................. (14)}$$

$C_{O,water}^*$ in Eq. (11), which was equivalent to a saturated oxygen concentration in water during aeration treatment practices, was measured by a DO meter and resulted in $7.4 \times 10^{-3}$ kg/m$^3$ at temperature of 298 K. The $h_B^*$ value in Eq. (13) was obtained from the relationship between the dissolved oxygen concentrations in water and liquid paraffin after a hard shaking between water with various oxygen concentrations and degassed liquid paraffin in a closed vessel without air. The volumes of water and liquid paraffin were $1.6 \times 10^{-4}$ m$^3$ and $8.0 \times 10^{-5}$ m$^3$, respectively. The relationship between dissolved oxygen concentrations in water and liquid paraffin is shown in **Fig. 6**. It was found that the value of $h_B^*$ in this study was 1.8.

After the oxygen-saturated liquid paraffin by aeration and oxygen-saturated liquid paraffin to degassed water is given by the oxygen balance in water as follows,

$$\frac{dC_{O,water}}{dt} = K_{O,water-L}a_{water}(C_{O,water} - C_{O,water}^*) - C_{O,water}^* \quad \text{................. (9)}$$

where $C_{O,water}$, $C_{O,water}^*$ and $C_{O,water}^*$ are oxygen concentrations in water, in equilibrium with oxygen in air and in equilibrium with oxygen in liquid paraffin, respectively. The first and second terms of the right side in Eq. (9) indicate the oxygen transfer rates from air to water (A and B in Fig. 5) and that from liquid paraffin to water (D in Fig. 5), respectively. In this study, the oxygen concentration in liquid paraffin is assumed to be kept saturated due to the sufficient oxygen transfer from air through the top blowing lance to liquid paraffin (C in Fig. 5).

Integration of Eq. (9) under the initial condition of $C_{O,water} = C_{O,water,0}$ led to the following equations.

$$\frac{(P_1 - C_{O,water})}{(P_1 - C_{O,water,0})} = \exp(-P_1t) \quad \text{................. (10)}$$

$$P_1 = \left(K_{O,water-L}a_{water}C_{O,water}^* + K_{O,water-L}a_{water}C_{O,water}^*\right)/\left(K_{O,water-L}a_{water} + K_{O,water-L}a_{water}\right) \quad \text{................. (11)}$$

$K_{O,water-L}$ can be expressed by Eq. (13) as well as Eq. (3).

$$C_{O,water} = C_{O,water}^* \quad \text{................. (14)}$$

$C_{O,water}^*$ in Eq. (11), which was equivalent to a saturated oxygen concentration in water during aeration treatment practices, was measured by a DO meter and resulted in $7.4 \times 10^{-3}$ kg/m$^3$ at temperature of 298 K. The $h_B^*$ value in Eq. (13) was obtained from the relationship between the dissolved oxygen concentrations in water and liquid paraffin after a hard shaking between water with various oxygen concentrations and degassed liquid paraffin in a closed vessel without air. The volumes of water and liquid paraffin were $1.6 \times 10^{-4}$ m$^3$ and $8.0 \times 10^{-5}$ m$^3$, respectively. The relationship between dissolved oxygen concentrations in water and liquid paraffin is shown in **Fig. 6**. It was found that the value of $h_B^*$ in this study was 1.8.

After the oxygen-saturated liquid paraffin by aeration and oxygen-saturated liquid paraffin to degassed water is given by the oxygen balance in water as follows,
hard in the closed vessel, the oxygen concentration in water was measured by the DO meter. The oxygen concentration, \( C_{O,\text{oil}} \), in liquid paraffin in equilibrium with air was calculated by substituting \( V_{w}/V_{\text{oil}}=(1.6\times10^{-3})/(8.0\times10^{-3}) \), the measured \( C_{O,w,b}, C_{O,w,a} \) and \( C_{O,\text{oil}}=1.8 \) into Eq. (15), which was the equation for mass balance of oxygen between water and liquid paraffin.

\[
C_{O,\text{oil}} V_{\text{oil}} + C_{O,w} V_{w} = C_{O,w,b} V_{w} + C_{O,\text{oil}} V_{\text{oil}} \tag{15}
\]

Table 3 shows the calculated \( C_{O,\text{oil}} \). The average \( C_{O,\text{oil}} \) value became \( 11.6 \times 10^{-3} \) kg/m\(^3\). Thus, \( C_{O,w} \) can be obtained from the product of \( h_{o}^* \) by \( C_{O,\text{oil}} \), that is, \( 1.8 \times 11.6 \times 10^{-3} = 20.9 \times 10^{-3} \) kg/m\(^3\).

According to Higbie’s penetration theory, the liquid/liquid mass transfer coefficient, \( k_{ij} \), of i-component in liquid j is given by

\[
k_{ij} = \frac{2 \{D_{ij} \left( \pi/3 \right) \}^{1/2}}{t_{exprj}} \tag{16}
\]

As there is no slip at the liquid/liquid interface, each \( t_{exprj} \) value of liquid j (=liquid paraffin, water) is assumed to be equal. Then, Eqs. (3) and (13) leads to

\[
1/K_{B,L-L} = a \left\{ \frac{1}{1/\left(D_{B,w}\right)^{1/2} + h_{B}^* \left(D_{B,\text{oil}}\right)^{1/2}} \right\} \tag{3'}
\]

\[
1/K_{O,L-L} = a \left\{ \frac{1}{1/\left(D_{O,w}\right)^{1/2} + h_{O}^* \left(D_{O,\text{oil}}\right)^{1/2}} \right\} \tag{3''}
\]

\( K_{O,L-L} \) in Eq. (13”) was calculated by using the measured \( K_{B,L-L}, h_{B}^* \) and \( h_{O}^* \) values and estimating \( D_{B,w}, D_{B,\text{oil}}, D_{O,w} \) and \( D_{O,\text{oil}} \) from the Wilke-Chang equation as well as the previous section. Finally, \( K_{O,G-L,G-L} \) was able to be obtained from substituting the above calculated \( K_{O,L-L} \) into Eq. (10) and using the trial and error method.

3.2. Effect of Top/bottom Blowing Rate on Liquid/liquid and Gas/liquid Mass Transfer Rates

Figure 7 shows the relationship between the overall liquid/liquid mass transfer capacity coefficient of benzoic acid, namely, \( K_{B,L-L,aL-L} \) and gas flow rate from the top blowing lance. Gas flow rate through the bottom blowing nozzles was also varied to 30, 50, and \( 70 \times 10^{-3} \) Nm\(^3\)/min. \( V_{\text{oil}} \) was kept to be \( 1.0 \times 10^{-3} \) m\(^3\), that is, \( V_{w}/V_{\text{oil}}=0.093 \). The liquid/liquid mass transfer rate increased with the increase in \( Q_{T} \) for both \( D=0.350 \) m (upper) and 0.450 m (lower). In the case of \( Q_{T} \) above \( 120 \times 10^{-3} \) m\(^3\)/min for \( D=0.350 \) m, the increase in \( Q_{b} \) led to the increase in the liquid/liquid mass transfer rate, whereas there was little \( K_{B,L-L,aL-L} \) increase with the increasing \( Q_{b} \) values for \( D=0.450 \) m. Under the condition of the same \( Q_{T} \) and \( Q_{b} \) values, \( K_{B,L-L,aL-L} \) and its increasing rate for \( D=0.450 \) m to \( Q_{T} \) were lower than that for \( D=0.350 \) m. Schematic views at \( D=0.350 \) m and 0.450 m are shown in Fig. 8. As there is a longer distance between air/water zone in the center and liquid paraffin near the wall in the case of \( D=0.450 \) m, momentum formed in the air/water zone did not transferred well to liquid paraffin near the wall and motion of liquid paraffin remained weak similar to a dead zone. However, as for \( D=0.350 \) m, the momentum transport from the air/water zone to the liquid paraffin region was smooth and contact of liquid paraffin with water could be active because of a shorter vessel diameter. An enhancement in momentum of liquid paraffin resulted in the increase in the liquid/liquid mass transfer coefficient and interfacial area and finally increased the liquid/liquid mass transfer rate.

The relationship between the overall gas/liquid mass

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**Table 3. Calculation of \( C_{O,\text{oil}} \)\(^* \) (unit: kg/m\(^3\))**

| Run No. | Water (measured) | Liquid paraffin (calculated) |
|---------|------------------|-----------------------------|
|         | \( C_{O,w,b} \)  | \( C_{O,w,a} \)  | \( C_{O,\text{oil}} \)  | \( C_{O,\text{oil}} \)  |
| 1       | 3.70             | 7.41                        | 11.54                       | 4.12                       |
| 2       | 2.72             | 6.42                        | 10.96                       | 3.57                       |
| 3       | 3.02             | 7.08                        | 12.05                       | 3.93                       |
| 4       | 1.97             | 5.96                        | 11.28                       | 3.31                       |
| 5       | 3.46             | 7.41                        | 12.02                       | 4.12                       |
| 6       | 3.61             | 7.42                        | 11.74                       | 4.12                       |
| Average | 3.08             | 6.95                        | 11.60                       | 3.86                       |
transfer capacity coefficient of oxygen, that is, \( K_{O,G-L} \), and \( Q_T \) is shown in Fig. 9. As seen in the upper (\( D = 0.350 \text{ m} \)) graph and lower (\( D = 0.450 \text{ m} \)) graph in Fig. 9, the gas/liquid mass transfer rate increased with the increase in \( Q_T \) or \( Q_B \), and the increasing rates for \( D = 0.350 \text{ m} \) to \( Q_T \) were lower than those for \( D = 0.450 \text{ m} \), which was contrary to the liquid/liquid mass transfer rate in Fig. 7. However, as for the bottom blowing, the difference in \( K_{O,G-L} \) became reduced with the increase in \( Q_T \) values, which meant the top blowing became dominant in the oxygen transfer test. It is due to the fact that the enhancement in \( Q_B \) leads to insufficient time for bottom blown air to pass through water and to absorb oxygen from the air.

### 3.3. Contours of Liquid/liquid and Gas/liquid Mass Transfer Rates

Contours of \( K_{B,L-L} \) is shown in Fig. 10 based on Fig. 7. \( V_{oil}/V_w \) was fixed at 0.093 (–). The increasing \( Q_T \) led to the decreasing \( Q_B \) for the same \( K_{B,L-L} \) lines at \((10^3 Q_B)^{0.5} < 8 \). The minimum distance, \( l \), between the origin and an equal \( K_{B,L-L} \) line was connected with a dashed line. Here, \( l \) means the minimum value of \( Q_T + Q_B \) for a given \( K_{B,L-L} \) due to \( l = \min \{ (Q_T^{1/2})^2 + (Q_B^{1/2})^2 \}^{1/2} \). At the condition of \((10^3 Q_T)^{0.5} > 5 \), the \( Q_B \) value of the minimum dashed line was kept at \((10^3 Q_B)^{0.5} \) around 6.3, that is, \( Q_B \approx 4.0 \times 10^{-2} \text{ Nm}^3/\text{min} \). It might be interesting to note that the bottom blowing rate is kept almost constant for a given liquid/liquid mass transfer rate.

Figure 11 shows contours of \( K_{O,G-L} \) without liquid paraffin. Each contour had almost the same tendency as that of \( K_{B,L-L} \) in Fig. 10 and the \( Q_B \) value of the minimum dashed line became about \( 4.0 \times 10^{-2} \text{ Nm}^3/\text{min} \). At the condition of \( Q_B > 4.0 \times 10^{-2} \text{ Nm}^3/\text{min} \), the bottom blown gas out of water disturbed the oxygen absorption at the air/water interface due to the top blown oxygen and suppressed the increase in the mobility between liquid paraffin and water. On the other hand, at the condition of \( Q_B < 4.0 \times 10^{-2} \text{ Nm}^3/\text{min} \), the decrease in the bath motion by the bottom blowing reduces the oxygen absorption at the air/water interface and the liquid/liquid motion. However, the threshold value of \( Q_B \) seemed to depend on the vessel dimension.

### 3.4. Effect of Volumetric Ratio of Liquid Paraffin to Water on Liquid/liquid and Gas/liquid Mass Transfer Rates

The relationship between the overall liquid/liquid mass transfer capacity coefficient and a volumetric ratio of liquid

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**Fig. 8.** Schematic diagram of mixing pattern among gas and two immiscible liquids in converter typed vessels.

**Fig. 9.** Relationship between gas/liquid mass transfer capacity coefficient and gas flow rate from a top blowing lance.

**Fig. 10.** Contours of liquid/liquid mass transfer capacity coefficient.
paraffin to water is shown in Fig. 12. Total gas flow rate was changed between $160 \times 10^{-3}$ and $180 \times 10^{-3}$ m$^3$/min. $K_{B,L - L}$ increased with the increase in $V_{oil}/V_w$ due to an increasing interfacial area between liquid paraffin and water except for $V_{oil}/V_w=0.46$ in the upper graph ($D=0.350$ m). The thicker layer of liquid paraffin at $V_{oil}/V_w=0.46$ of Fig. 12. The thicker layer of liquid paraffin at $V_{oil}/V_w=0.46$ of Fig. 12. $D=0.350$ m suppressed the increase in the interfacial area between liquid paraffin and water due to the increasing stagnation zone of liquid paraffin. $K_{B,L - L}$ also increased with the increase in $Q_t/Q_b$, especially in the lower graph ($D=0.450$ m). $K_{B,L - L}$ at $Q_t/Q_b=90/70$ became smaller than the other larger top/bottom blowing ratio, especially in $V_{oil}/V_w \geq 0.28$. It was because the bottom blowing gas, which passed through the bath center, had a poor effect to accelerate the interfacial area between liquid paraffin near the vessel wall and water compared with the top blowing gas.

The relationship between the overall gas/liquid mass transfer capacity coefficient and the volumetric ratio of liquid paraffin to water is shown in Fig. 13. Total gas flow rate was also kept between $160 \times 10^{-3}$ and $180 \times 10^{-3}$ m$^3$/min. Contrary to $K_{B,L - L}$ in Fig. 12, $K_{O,G - L}$ decreased with the increase in $V_{oil}/V_w$ due to the increase in thickness of liquid paraffin which reduced the free surface of water and oxygen transfer through air from the top blowing lance (A in Fig. 5). However, the $K_{O,G - L}$ values at $Q_t/Q_b=90/70$ and $Q_t/Q_b=90/70$ increased at $V_{oil}/V_w=0.46$. It could be due to the increase in the contribution of bottom blowing gas to oxygen transfer in water bath (B in Fig. 5). As the adverse trend of $K_{B,L - L}$ in Fig. 12, $K_{O,G - L}$ values at $Q_t/Q_b=90/70$ were larger than the other top/bottom blowing condition at $V_{oil}/V_w \leq 0.093$. The bottom blowing was estimated to be more effective in enhancing the gas/liquid mass transfer.

3.5. Relationship between Liquid/liquid and Gas/liquid Mass Transfer Rates

Figure 14 shows the relationship between $K_{B,L - L}, K_{O,G - L}$ divided by $V_{oil}$ and $K_{O,G - L}$ divided by $V_{oil}$. $K_{B,L - L}$ divided by $V_{oil}$ represents the liquid paraffin efficiency for the liquid/liquid mass...
transfer rate. In the case of $V_{oil}/V_w=0.093 \pm 0.003$ and $Q_t+Q_b$ from 30 to 250 ($10^{-3}$ Nm$^3$/min), there was a positive correlation between liquid/liquid and gas/liquid mass transfer rates with large scattering values. The increasing rate of the liquid/liquid mass transfer to the gas/liquid one at $D=0.350$ m was larger than that at $D=0.450$ m. It is because the smaller vessel cross-sectional area ($D=0.350$ m) stirred liquid/liquid layers more homogeneously, especially near the vessel wall as illustrated by Fig. 8.

However, when $Q_t+Q_b$ was between 160 and 180 ($10^{-3}$ Nm$^3$/min), that is, almost the same blowing rate, a negative correlation between liquid/liquid and gas/liquid mass transfer rates was recognized at each $V_{oil}/V_w$. The top blowing was more effective in liquid/liquid mass transfer as seen in Fig. 12, whereas the bottom blowing rate contributed to gas/liquid mass transfer as shown in Fig. 13.

Thus, a roughly positive correlation between liquid/liquid and gas/liquid mass transfer rates was found in the wide range of experimental condition, and the tendency was opposite at the same total gas blowing rate and $V_{oil}/V_w$ due to the different contribution to the mass transfer rate between top and bottom blowing.

The next problem is to analyze a correlation between gas/liquid and liquid/liquid mass transfer rates in multiple industrial converters by summarizing the typical gas/metal and slag/metal reaction rates throughout a wide range of top/bottom blowing rates and volumes of molten slag to steel melt.

4. Conclusions

A cold model study on a mass transfer rate of benzoic acid between water and liquid paraffin, which simulated a slag/metal system and a mass transfer rate of oxygen among water, liquid paraffin and air like a gas/metal system was carried out under the same operational condition of converter-typed vessels. Results obtained in this study were described as follows;

(1) A calculation procedure of the gas/liquid mass transfer capacity coefficient was developed on the basis of the liquid/liquid mass transfer capacity coefficient.

(2) The liquid/liquid mass transfer rate increased with the increase in a top blowing rate, but the increasing rate of a larger vessel to the top blowing rate was lower than that of a smaller one.

(3) The gas/liquid mass transfer rate increased with the increase in both of the top and bottom blowing rates, but its difference became reduced with the increase in the top blowing rate.

(4) The bottom blowing rate to minimize the sum of the top and bottom blowing rates was almost constant for a given gas/liquid or liquid/liquid mass transfer rate.

(5) The liquid/liquid mass transfer rate increased and the gas/liquid one decreased with the increase in the liquid paraffin volume ratio to water.

(6) There was a roughly positive correlation between the liquid/liquid and gas/liquid mass transfer rates throughout a wide range of top and bottom blowing rates, but the tendency was the opposite under the condition of the same paraffin volume and total blowing rate.

Nomenclature

$a(=\pi^{1/2}\exp(1/2))$: constant
$a_{g-1}$: interfacial area between air and water per water volume (m$^2$/m$^3$)
$a_{L-1}$: interfacial area between liquid paraffin and water per water volume (m$^2$/m$^3$)
$C_{B,oil}$: benzoic acid concentration in liquid paraffin (kg/m$^3$)
$C_{B,w}$: benzoic acid concentration in water (kg/m$^3$)
$C_{B,w}$*: benzoic acid concentration in water in equilibrium with that in liquid paraffin (kg/m$^3$)
$C_{O,oil}$: oxygen concentration in liquid paraffin (kg/m$^3$)
$C_{O,oil}$*: oxygen concentration in liquid paraffin in equilibrium with oxygen in air (kg/m$^3$)
$C_{O,w}$: oxygen concentration in water (kg/m$^3$)
$C_{O,w}$*: oxygen concentration in water in equilibrium with oxygen in liquid paraffin (kg/m$^3$)
$C_{O,w,G-L}$: oxygen concentration in water in equilibrium with oxygen in air (kg/m$^3$)

$D$: vessel inner diameter (m)
$D_B$: bottom diameter (m)
$D_{B,oil}$: benzoic acid diffusivity in liquid paraffin (m$^2$/s)
$D_{B,w}$: benzoic acid diffusivity in water (m$^2$/s)
$D_{i,j}$: i-component diffusivity in j-liquid (m$^2$/s)
$D_{O,oil}$: oxygen diffusivity in liquid paraffin (m$^2$/s)
$D_{O,w}$: oxygen diffusivity in water (m$^2$/s)

$h_B^*(=C_{B,w}/C_{B,oil})$: partition ratio of benzoic acid between water and liquid paraffin

$h_O^*(=C_{O,w}/C_{O,oil})$: partition ratio of oxygen between water and liquid paraffin

$H$: bath depth (m)

$k_{B,w,L-1}$: water film coefficient of benzoic acid transfer (m/s)
$k_{i,j}$: j-liquid film coefficient of i-component transfer (m/s)

$k_{o,i,j}$: liquid film coefficient of oxygen transfer (m/s)

$k_{O,w,L − L}$: water film coefficient of oxygen transfer (m/s)

$k_{O,oil,L − L}$: liquid paraffin film coefficient of oxygen transfer (m/s)

$K_{B,L − L}$: overall mass transfer coefficient of benzoic acid between liquid paraffin and water (m/s)

$K_{O,G − L}$: overall mass transfer coefficient of oxygen between air and water (m/s)

$K_{O,L − L}$: overall mass transfer coefficient of oxygen between liquid paraffin and water (m/s)

$K_{O,L − L}$: overall mass transfer capacity coefficient of oxygen between liquid paraffin and water (s$^{-1}$)

$L$: lance height (m)

$Q_{B}$: bottom blowing rate (10$^{-3}$ m$^{3}$/min)

$Q_{T}$: top blowing rate (10$^{-3}$ m$^{3}$/min)

$t_{exp,j}$: exposure time of j-liquid at a liquid/liquid interface (s)

$V_{oil}$: oil volume (10$^{-3}$ m$^{3}$)

$V_{W}$: water volume (10$^{-3}$ m$^{3}$)

$\alpha$: total amount of benzoic acid dissolved in liquid/liquid system (kg)

$\pi$: circular constant

REFERENCES

1) K. N. Subramanian and F. D. Richardson: *J. Iron Steel Inst.*, 206 (1968), 576.
2) P. Patel, M. G. Frohberg and D. Papamantellos: *Trans. AIME*, 245 (1969), 855.
3) K. Nakaniishi, Y. Kato, T. Nozaki and T. Emi: *Tetsu-to-Hagané*, 66 (1980), 1307.
4) I. Sawada, T. Ohashi and H. Kajiwara: *Tetsu-to-Hagané*, 70 (1984), S161.
5) S. H. Kim and R. J. Fruehan: *Metall. Trans. B*, 18B (1987), 381.
6) K. Ogawa, S. Ito, T. Onoe T. Makino and K. Narita: *Tetsu-to-Hagané*, 70 (1984), A181.
7) Y. Oga, S. Taniguchi and J. Kikuchi: *Tetsu-to-Hagané*, 71 (1985), S897.
8) S. Endo and M. Hasegawa: *Tetsu-to-Hagané*, 71 (1985), S899.
9) Y. Okada, S. Taniguchi and J. Kikuchi: *Tetsu-to-Hagané*, 73 (1987), S946.
10) S. Paul and D. N. Ghosh: *Metall. Trans. B*, 17B (1986), 461.
11) V. Singh, S. N. Lenka, S. K. Ajmani, C. Bhanu and S. Pathak: *ISIJ Int.*, 49 (2009), 1889.
12) K. Nakaniishi, K. Saito, T. Nozaki, Y. Kato, K. Suzuki and T. Emi: *Steelmaking Conf. Proc.*, 65 (1982), 101.
13) J. G. Chang, D. W. Zhong, F. Y. Yi and X. K. Di: *Scand. J. Metall.*, 16 (1987), 42.
14) Z. H. Wu, Z. S. Zou and W. Wu: *Acta Metall. Sin.*, 18 (2005), 91.
15) S. Inada and T. Watanabe: *Tetsu-to-Hagané*, 63 (1977), 37.
16) R. J. Fruehan and L. j. Martonik: Proc. 3rd Int. Iron and Steel Cong., ASM, The Netherlands, (1978), 229.
17) A. Fukuzawa, Y. Fukuzawa, K. Kamihira, I. Morinaka and A. Kasahara: *Tetsu-to-Hagané*, 68 (1982), S126.
18) S. H. Kim and R. J. Fruehan: *Metall. Trans. B*, 18B (1987), 673.
19) D. Guo and G. A. Irons: *Metall. Mater. Trans. B*, 31B (2000), 1447.
20) N. Bessho, S. Taniguchi and J. Kikuchi: *Tetsu-to-Hagané*, 71 (1985), 1623.
21) K. Sakaguchi and K. Ito: *ISIJ Int.*, 35 (1995), 1348.
22) Y. Kato, T. Fujii, N. Harada, H. Nakamura and Y. Habu: Proc. 4th Process Technology Conf., ISS-AIME, Chicago, (1983), 121.
23) S. Inada and T. Watanabe: *Tetsu-to-Hagané*, 62 (1976), 807.
24) S. C. Koria and A. George: *Ironmaking Steelmaking*, 15 (1988), 127.
25) S. Kojima, M. Yoshida, T. Iwata and H. Take: *Kawasaki Steel Gihoh*, 19 (1987), 1.
26) S. Horiochi, M. A. Uddin, Y. Kato Y. Takahashi and Y. Uchida: *ISIJ Int.*, 54 (2014), 87.
27) R. B. Bird, W. E. Stewart and E. N. Lightfoot: *Transport Phenomena*, 2nd ed., John Wiley & Sons, Inc., New York, (2007), 530, 560.