In order to find out effect of operating factors on mixing pattern which affects liquid/liquid mass transfer rate drastically, cold model experiment was carried out with liquid paraffin or tetradecane as a dispersed phase and ion-exchanged water as a continuous phase in a mechanically stirred vessel. There exist three types of liquid/liquid mixing pattern in a mechanical agitation. I: region where each liquid phase separates and has no dispersion, II: region where vortex of dispersed phase (liquid/liquid interface) arrives at impeller position and its dispersion begins into continuous phase, III: region where gas/liquid interface as well as liquid/liquid one arrives at impeller position and dispersion occurs heavily. The transition of I–II accelerated along with the increases in rotation speed, ratio of dispersion phase volume to continuous one, density of dispersion phase, impeller diameter and vessel diameter, and the decrease in impeller depth. The transition of II–III accelerated along with the increases in rotation speed, density of dispersion phase and impeller diameter, and the decrease in impeller depth.

The multi regression equation for the transition of I–II is expressed as,

\[ H - H_0 \propto N^{0.52} \left( \frac{V_{oil}}{V_w} \right)^{0.36} d_{oil}^{1.71} D^{0.40} \rho_{oil}^{4.43} \]

where \( H \): distance between free surface of oil and upper part of impeller (mm), \( H_0 \): bath depth of dispersed phase(mm), \( N \): rotation speed(rpm), \( V_{oil} / V_w \): ratio of dispersion phase volume to continuous one(–), \( d_{oil} \): impeller diameter(mm), \( D \): vessel diameter(mm), \( \rho_{oil} \): density of dispersion phase(kg/m\(^3\)), whereas that on transition of II–III is \( H \propto N^{2.18} d_{oil}^{1.96} \rho_{oil}^{1.33} \).

KEY WORDS: steelmaking; mechanical stirring; slag-metal reaction; mixing pattern; mass transfer.

1. Introduction

Slag/metal reaction caused by solid/liquid or liquid/liquid system is one of the most basic and important practices to remove the impurities in steel melt, typically known as gas injection\(^1\) or mechanical stirring.\(^2\)–\(^4\) Cold model experiment has been a helpful method to understand the slag/metal transport phenomena. Therefore, there are many studies in this domain.\(^5\) For mechanical stirring operation, Nakai et al.\(^6\) showed that desulfurization rate increased remarkably when vortex caused by mechanical stirring came at the impeller position and the flux dispersed in steel melt. There are also studies of the effect of baffles\(^7,8\) on the dispersion behavior\(^9,10\) of particles into liquid in a mechanically agitated bath.

On the other hand, in case of liquid/liquid mechanical stirring, it is likely that penetration of the dispersion layer into an impeller position affects liquid/liquid mass transfer rate as Nakai et al.\(^6\) indicated in the solid/liquid system. However, there are few studies on mixing pattern vs. operating factors of liquid/liquid system during mechanical agitation processes in the field of steelmaking except study on impeller diameter and mechanical offset suitable for complete dispersion of the dispersion phase worked in the field of chemical engineering.\(^11\)

In this water model study, liquid paraffin and tetradecane were chosen as dispersion phase and effect of operating factors such as rotation speed, impeller depth were made clear in a mechanically agitated vessel.

2. Experimental

Schematic view of experimental apparatus is shown in Fig. 1. Liquid paraffin or tetradecane as dispersion phase and ion-exchanged water as continuous phase were charged in an acrylic tank. Inner diameter of a vessel is denoted as \( D \) mm and bath depth of static continuous and dispersed phases is represented as \( H_0 \) mm. Four blades of impeller whose diameter is expressed as \( d_i \) mm, thickness as \( b_i \) mm and width as \( w_i \) mm was used as shown schematically in Fig. 2. The impeller was set in the central axis of the vessel. Visual observation was carried out to obtain a relation between characteristic mixing pattern and impeller position, which means vortex depth of liquid/liquid interface or
gas/liquid interface was measured with a ruler. Photography was made for liquid paraffin colored with oil-based ink.

Experimental conditions are shown in Table 1 where baselines are underlined. $D = H_0 = 400$ mm and $d_i, b_i, w_i = 116$ mm, 67 mm, 31 mm were used except the experiment where these factors were changed. Rotation speed, $N$ was changed 0–410 rpm, volumetric ratio of dispersed to continuous phase $V_{oil}/V_w$ was 0–5.0 $\times$ 10$^{-1}$, although its baseline was 1.2 $\times$ 10$^{-1}$. Densities of liquid paraffin and tetradecane used for the experiments were 828 and 763 kg/m$^3$, respectively. When static depths of liquid paraffin and water were defined as $H_{oil}$ and $H_w$, these values were calculated as Table 2 for $D = H_0 = 400$ mm and Table 3 for $D = H_0 = 300$ mm.

3. Results and Discussion

3.1. Mixing Patterns of Single Liquid Phase and Liquid/liquid Double Phases

Mixing patterns of water and liquid paraffin/water at $N = 189$ rpm and $H = 233$ mm are shown in Fig. 3. $V_{oil}/V_w$ of liquid/liquid equals to 1.2 $\times$ 10$^{-1}$. The formed vortex of a single liquid phase (Fig. 3(a)) is different from liquid/liquid phase (Fig. 3(b)). As shown in Fig. 3(b), liquid/liquid interface reaches the impeller, whereas gas/liquid one drawn in dotted line exists upward. The interface depth of liquid/liquid is larger and that of gas/liquid in liquid/liquid flow is less than that of gas/liquid in a single phase.

3.2. Mixing Pattern of Liquid/liquid System

When impeller depth is changed at $N = 146$ rpm and $V_{oil}/V_w = 1.2 \times 10^{-1}$, mixing pattern is also changed as shown in Fig. 4. Three types of mixing patterns in liquid/liquid system are recognized. I is the region where liquid/liquid interface does not arrive at the impeller (Fig. 4(a)), II is the region where liquid/liquid interface attains at the impeller position and a part of liquid paraffin disperses in water (Fig. 4(b)) and III is the region where gas/liquid interface touches the impeller (Fig. 4(c)). Transitions of I$\rightarrow$II$\rightarrow$III occur along with the decrease in impeller depth.

The above three mixing patterns are recognized when rotation speed is changed at $V_{oil}/V_w = 1.2 \times 10^{-1}$ and $H = 233$ mm in Fig. 5. Figure 5(a) is the region I at $N = 137$ rpm, Fig. 5(b) is II at $N = 231$ rpm and Fig. 5(c) is III at $N = 360$ rpm. Transitions of I$\rightarrow$II$\rightarrow$III arise with the increase in rotation speed.

3.3. Effect of Operating Factors on Liquid/liquid Mixing Pattern

Mixing patterns and their transitions in the cases of various $N$ and $H$ under $V_{oil}/V_w = 1.2 \times 10^{-1}$ are shown in Fig. 6. Liquid paraffin and tetradecane were used for a dispersion phase. As shown in transition curves of I$\rightarrow$II $\rightarrow$III $\rightarrow$II $\rightarrow$III occur along with the decrease in impeller depth. There indicate that tetradecane is harder to form the vortex than the liquid paraffin. It seems to be due to the density differences, that is, the density of liquid paraffin is larger than tetradecane.

The mixing patterns and their transitions for various $V_{oil}/V_w$ and $N$ are shown in Fig. 7 where the dispersion phase was
liquid paraffin. To transit from I to II, the larger rotation speed was required along with the decrease in \( V_{oil}/V_{w} \), which implies that the liquid/liquid interface depth decreases with smaller \( V_{oil}/V_{w} \) at the same \( N \) and \( H \) in the region I. However, the transitions of II–III had no change even if \( V_{oil}/V_{w} \) was changed. It was found that the region where the vortex arrives at the impeller in a single water phase expressed by \( V_{oil}/V_{w} = 0 \) exists at the transition of II–III.

As \( H_{oil} \) and \( H_{w} \) have different values according to \( V_{oil}/V_{w} \) as shown in Tables 2 and 3, it is effective to rearrange the transition of I–II of Fig. 7 with \( H-H_{oil} \) instead of \( H \). Figure 8 shows the mixing patterns and their transition. The transition curve of a single water phase was also drawn here. The transition curves of I–II approached II–III according as \( V_{oil}/V_{w} \) approached 0.

The mixing patterns and their transitions for tetradecane/water mixing are shown in Fig. 9. The transition curves of

![Fig. 3. Comparison between mixing patterns of mechanical stirring in single and two liquid phases (N = 189 rpm, H = 233 mm, D = H₀ = 400 mm).](image)

![Fig. 4. Change in mixing pattern according to impeller position (N = 146 rpm, \( V_{oil}/V_{w} = 1.2 \times 10^{-1} \)).](image)

![Fig. 5. Change in mixing pattern according to rotating speed (H = 233 mm, \( V_{oil}/V_{w} = 1.2 \times 10^{-1} \)).](image)

![Fig. 6. Mixing pattern and its transition for different dispersion phase.](image)

![Fig. 7. Mixing pattern and its transition according to \( V_{oil}/V_{w} \) (liquid paraffin).](image)
I–II approached to II–III, which is the same tendency as shown in Fig. 8.

Based on these results, the schematic views of mixing patterns and their transitions in case of various $V_{\text{oil}}/V_w$ are drawn in Fig. 10. The upper stage is for I and II, whereas lower one is for III. When $V_{\text{oil}}/V_w$ was larger, the vortex of dispersed phase was formed deeply and its mixing pattern became II. However, under the same $N$ and $H$, mixing pattern changed from II to I for smaller $V_{\text{oil}}/V_w$. On the other hand, the mixing pattern of III and its transition to II was independent of $V_{\text{oil}}/V_w$.

3.4. Effect of Impeller and Vessel Diameters on Mixing Pattern

Figure 11 shows the mixing patterns and their transitions where impeller diameter was changed. Both of D and $H_0$ were fixed to 400 mm and $V_{\text{oil}}/V_w$ was also kept at $1.2 \times 10^{-1}$. Under larger impeller diameter, the vortex was formed deeply and the transitions of I–II and II–III occurred at lower rotation speed, which means larger impeller is more effective for liquid/liquid mixing.

The mixing patterns and their transitions are shown in Fig. 12 when both of vessel diameter and bath depth were changed. Impeller size of $d_i$, $b_i$, and $W_i$ was fixed to 116 mm, 67 mm and 31 mm, respectively, and $V_{\text{oil}}/V_w$ was also kept at $1.2 \times 10^{-1}$. It was found that larger D and $H_0$ required less rotation speed to transit the mixing pattern from I to II, although the transition of II–III was not affected by the vessel size and bath depth.

3.5. Quantitative Relations Among Operating Factors on Transitions of I–II and II–III

A multi-regression analysis was carried out in order to find the relation among operating factors quantitatively. Using the data of sections 3.3 and 3.4, the equation of transition of I–II was expressed as follows:

$$H - H_{\text{oil}} = 10^{-0.4 \times 10^{-1} \cdot (V_{\text{oil}}/V_w)^{0.52}} \cdot d_i^{0.71} \cdot D^{0.399} \cdot \rho_d^{-0.43} \cdots (1)$$

where correlation coefficient, $R^2$ equals 0.923. As seen from Eq. (1), $N$, $V_{\text{oil}}/V_w$, $d_i$, $D$ and $\rho_d$ had positive correlation with $H - H_{\text{oil}}$. 

Fig. 8. Mixing pattern and its transition according to $V_{\text{oil}}/V_w$ (liquid paraffin).

Fig. 9. Mixing pattern and its transition according to $V_{\text{oil}}/V_w$ (tetradecane).

Fig. 10. Change in mixing pattern according to $V_{\text{oil}}/V_w$.

Fig. 11. Mixing pattern and its transition according to impeller.

Fig. 12. Mixing pattern and its transition according to vessel size.
On the other hand, the transition of II–III is not affected by $V_{\text{oil}}/V_{\text{w}}$, $H_{\text{oil}}$ and $D$ as shown in Figs. 7, 8 and 12. Therefore, a multi-regression analysis was carried out without the above factors and equation for transition of II–III was given as follows:

$$H = 10^{-111} N^{2.18} d_{i}^{1.96} \rho_{d}^{1.33} \quad ...$$

where correlation coefficient, $R^2$ equals 0.99. As seen from Eq. (2), $N$, $d_{i}$ and $\rho_{d}$ has positive correlation with $H$.

The quantitative relations of the transitions of I–II and II–III were obtained from Eqs. (1) and (2), respectively. The regions I, II and III in this experiment have been affirmed by pilot plant test carried out by liquid slag and metal. However, the dimensional analysis with dimensionless numbers including more factors than this experiment is needed in order to apply the quantitative relation to the slag/metal system.

4. Conclusions

Liquid/liquid cold model experiments of mixing pattern and its transition was carried out with liquid paraffin or tetradecane as a dispersed phase and ion-exchanged water as a continuous phase in a mechanically stirred vessel.

(1) Vortex of dispersed phase in liquid/liquid flow was able to arrive at impeller, although vortex of a single phase flow did not penetrate into impeller position under the same operating condition.

(2) There existed three types of liquid/liquid mixing patterns in a mechanical agitation. I: region where each liquid phases separate and have no dispersion, II: region where vortex of dispersed phase (liquid/liquid interface) arrives at impeller position and its dispersion begins into continuous phase, III: region where gas/liquid interface in addition to liquid/liquid interface arrives at impeller position and dispersion occurs hard.

(3) The transition of I–II was accelerated along with the increases in rotation speed, ratio of dispersion phase volume to continuous one, density of dispersion phase, impeller diameter and vessel diameter, and the decrease in impeller depth.

(4) The transition of II–III was accelerated along with the increases in rotation speed, density of dispersion phase and impeller diameter, and the decrease in impeller depth.

(5) The multi regression equation on transition of I–II was as follows:

$$H - H_{\text{oil}} \propto N^{2.52} (V_{\text{oil}}/V_{\text{w}})^{0.36} d_{i}^{1.71} D^{0.46} \rho_{d}^{1.43}$$

where $H$: impeller depth(mm), $H_{\text{oil}}$: bath depth of dispersed phase(mm), $N$: rotation speed(rpm), $V_{\text{oil}}/V_{\text{w}}$: ratio of dispersion phase volume to continuous one(–), $d_{i}$: impeller diameter(mm), $D$: vessel diameter(mm), $\rho_{d}$: density of dispersion phase(kg/m$^3$).

(6) The multi regression equation on transition of II–III was as follows:

$$H \propto N^{2.18} d_{i}^{1.96} \rho_{d}^{1.33}$$

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