Comparison of Mixing Time Values between Gas Injections from Centered and Off-centered L-shaped Top Lance in the Presence of Swirl Motion

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1. Introduction

Many types of gas injection methods have extensively been used in the current steelmaking processes to homogenize the temperature and components of molten steel and to remove impurities and non-metallic inclusions from the molten steel.1,2) Bottom, top, and side gas injection methods are known to be basic ones. Of course, combinations of these basic methods are commonly employed in the real processes. Compared to information on the mixing characteristics of molten steel baths agitated by bottom and top gas injection, the effect of side gas injection on the mixing characteristics is not fully understood yet although the side gas injection is familiar with the AOD process.3)

A nozzle attached horizontally to the side wall of the reactor of the AOD process suffers from erosion and the weeping phenomenon sometimes takes place. In addition, although an optimum vertical nozzle position depends on the bath depth, changing the nozzle position is difficult as long as the nozzle is attached to the side wall of the reactor. These problems can readily be solved when a top lance is used. In previous papers3,5) the authors proposed a method of side gas injection through an L-shaped top lance and carried out water model experiments on the occurrence condition of a swirl motion of the deep-water wave type and on mixing time, \( T_m \). First, the exit of the L-shaped top lance was placed on the centerline of a cylindrical vessel containing de-ionized water.4) Mixing time of the bath was measured with an electrical conductivity meter. An empirical equation for the mixing time, \( T_m \), was proposed as a function of the vessel diameter, \( D \), bath depth, \( H_b \), nozzle immersion depth, \( d_{no} \), and the physical properties of the working fluids in the presence of the swirl motion. Second, a similar empirical equation was derived in the absence of the swirl motion.5) The mixing time was found to be significantly shortened under a certain condition in the presence of the swirl motion compared to the value in the absence of it.

Concerning the bottom gas injection from a single-hole bottom nozzle, mixing time becomes much shorter for an off-centered nozzle than for a centered nozzle.2) The reason is that the scale of the recirculating flow in the bath is enlarged in the former case. This fact suggests that the same result can be expected for an off-centered L-shaped top lance. The main objective of the present study therefore is to clarify whether this expectation is realized or not in the presence of the swirl motion of the deep-water wave type.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the experimental apparatus. The vessel diameters were \( D = 0.130, 0.200, \) and \( 0.300 \) m. De-ionized water and air were chosen as the working fluids. Water is commonly used as a model liquid for molten steel because its kinematic viscosity is nearly equal to that of the molten steel. Air was injected through an off-centered L-shaped top lance. The lance exit was placed at a radial distance of \( r = D/4 \). The inner and outer diameters of the lance, \( d_{in} \) and \( d_{ou} \), were \( 3.7 \times 10^{-3} \) m and \( 5.1 \times 10^{-3} \) m for \( D = 0.130 \) m, \( 4.1 \times 10^{-3} \) m and \( 6.4 \times 10^{-3} \) m for \( D = 0.200 \) m, and \( 3.7 \times 10^{-3} \) m and \( 5.1 \times 10^{-3} \) m for \( D = 0.300 \) m, respectively. The aspect ratio, \( H/D \), and the dimensionless immersion depth of the lance, \( H_m/D \), were varied as follows:

\[
H_L/D = 0.7, 1.0, 1.5 \dots \quad (1)
\]

\[
H_m/D = 0.1 \sim 0.7 \quad (H_L/D = 0.7)
\]

\[
= 0.1 \sim 1.0 \quad (H_L/D = 1.0, 1.5) \quad \dots \quad (2)
\]

The air flow rate, \( Q_{in} \), was adjusted with a mass flow controller from \( 100 \times 10^{-6} \) m\(^3\)/s to \( 1800 \times 10^{-6} \) m\(^3\)/s.

Mixing time was determined on the basis of the history of the electrical conductivity of a mixture of water and tracer in the bath. An aqueous KCl solution (1 mol/L) was used as a tracer. Figure 2 shows the definition of mixing time.

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the tracer. It was charged into the bath from a position just above the bath surface. The electrical conductivity was measured with an electrical conductivity meter. The mixing time was defined as the period from the moment of tracer charge to the moment at which the electrical conductivity finally crossed 0.95 $V_F$ or 1.05 $V_F$, as shown in Fig. 2. It should be noted that a scatter of $\pm 60\%$ is acceptable as long as the present definition for the mixing time is chosen.

3. Experimental Results and Discussion

3.1. Occurrence Condition for a Swirl Motion of the Deep-water Wave Type

The occurrence condition for this type of swirl motion was identified on a map as a function of the dimensionless immersion depth of the lance, $H_{in}/D$, and the gas flow rate, $Q_g$ (see Figs. 3 through 5). The swirl motions for the off-centered and centered top lances are denoted by open and solid circles, respectively. Such swirl motions did not occur under the remaining experimental conditions.

The swirl motion for the off-centered top lance is caused by bubbles leaving the lance exit and then impinging onto the bath surface region located near the centerline of the bath. The distance between the lance exit and the bath surface region increases with an increase in the vessel diameter, $D$. The horizontal penetration depth of the bubbles leaving the lance exit, $L_{H}$, is expressed by

$$L_{H} = 3.7 d_{in} F_{rm}^{1/3} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (3)$$

$$F_{rm} = \frac{\rho_{g} Q_{g}^{2}}{\rho_{L} g d_{in}^{5}} \quad \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots (4)$$

where $d_{in}$ is the inner diameter of the lance, $F_{rm}$ is the modified Froude number, $\rho_{g}$ is the density of the gas, $Q_{g}$ is the gas flow rate, $\rho_{L}$ is the density of the liquid, and $g$ is the acceleration due to gravity. Accordingly, the occurrence region of the swirl motion shifted in the high gas flow rate direction with an increase in the vessel diameter, $D$.

The occurrence region for the off-centered L-shaped top lance denoted by open circles, ○, shifted in the high gas flow rate direction compared to that for the centered L-shaped top lance denoted by solid circles, ●, as can be seen in Figs. 3 through 5. This is because the gas flow rate must be increased for making bubbles generated at the exit of the

![Fig. 3.](image1) Map for identifying the occurrence region of a swirl motion of the deep-water wave type ($D = 0.130 \text{ m} \text{ and } H_{in}/D = 1.0$).

![Fig. 4.](image2) Map for identifying the occurrence region of a swirl motion of the deep-water wave type ($D = 0.200 \text{ m} \text{ and } H_{in}/D = 1.0$).

![Fig. 5.](image3) Map for identifying the occurrence region of a swirl motion of the deep-water wave type ($D = 0.300 \text{ m} \text{ and } H_{in}/D = 1.0$).

![Fig. 6.](image4) Photographs of swirl motion ($D = 0.200 \text{ m}, H_{in}/D = 0.7, H_{al}/D = 0.4, Q_{g} = 400 \times 10^{-6} \text{ m}^3/\text{s}$).

![Fig. 7.](image5) Photographs of swirl motion ($D = 0.200 \text{ m}, H_{in}/D = 1.5, H_{al}/D = 0.4, Q_{g} = 300 \times 10^{-6} \text{ m}^3/\text{s}$).
off-centered lance reach the above-mentioned bath surface region near the centerline of the bath. The period of the swirl motion was independent of the lance exit position, while the amplitude decreased as the lance exit shifted from the center of the vessel to the off-centered position, as can be seen in Figs. 6 and 7.

Mixing time measurements were carried out under the conditions that the swirl motion occurred both for the centered and off-centered top lance positions. Each condition is denoted by a solid circle enclosed with an open circle, ○●, in Figs. 3 through 5. No experiment therefore was carried out for \( D = 0.300 \text{ m} \).

### 3.2. Comparison of Mixing Time Values between Centered and Off-centered L-shaped Top Lances

Figure 8 shows the measured mixing time values both for the centered and off-centered L-shaped top lances. The mixing time increased with an increase in the aspect ratio of the bath, \( H_L/D \), regardless of the lance exit position. Roughly speaking, the centered lance brought about a mixing time value shorter than that for the off-centered lance at \( H_L/D = 0.7 \), while the tendency was reversed at \( H_L/D = 1.5 \).

In order to show this tendency more clearly, a mixing time ratio, \( T_{m,\text{off-centered}}/T_{m,\text{centered}} \), was newly introduced and plotted in Figs. 9 and 10. The mixing time ratio decreased with an increase in \( H_L/D \). According to a previous paper, the swirl motion of the deep-water wave type exerts its negligibly small effect on the mixing time in a bath with \( H_L/D \) of greater than unity. That is, the mixing time in a bath for \( H_L/D > 1 \) is mainly governed by the scale of the recirculating flow in the bath. The scale is enlarged when the lance exit is located at an off-centered position. This is the reason why the mixing time ratio becomes smaller than unity even though the swirl motion is weakened for the off-centered lance.

Meanwhile, when the aspect ratio of the bath, \( H_L/D \), is smaller than unity, the swirl motion plays an essential role on the mixing of the bath. The swirl motion is stronger for the centered lance than for the off-centered lance. This is the main reason why the mixing ratio is greater than unity at \( H_L/D = 0.7 \).

In this note the relationship between the dimensionless immersion depth of the lance, \( H_{in}/D \), and the mixing time ratio was not discussed. It is necessary to collect more mixing time data for larger vessels for an understanding of the relationship.

### 4. Concluding Remarks

The mixing time ratio decreased with an increase in the aspect ratio of the bath, \( H_L/D \), as shown in Figs. 9 and 10. Changing the exit position of an L-shaped top lance in the radial direction is beneficial for shortening the mixing time in the presence of the swirl motion of the deep-water wave type only when the aspect ratio of the bath, \( H_L/D \), is greater than about unity.

### REFERENCES