Mixing Time in a Cylindrical Bath Agitated by Gas Injection through an L-shaped Top Lance in the Absence of Swirl Motion

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Experimental investigations are carried out on mixing time in a water bath agitated by side gas injection with an L-shaped lance. The mixing time is measured using an electrical conductivity sensor and an aqueous KCl solution as a tracer. Particular attention is paid to bath agitation under the conditions that any kinds of swirl motions of a bubbling jet do not appear. An empirical equation is proposed for the mixing time as a function of the gas flow rate, bath diameter, bath depth, and the physical properties of water by referring to a previously proposed empirical equation for mixing time in a bath agitated by J-shaped top lance gas injection. The equation is compared with an empirical equation proposed for a bath in the presence of a swirl motion of the deep-water wave type.

KEY WORDS: steelmaking; gas injection; mixing time; top lance; agitation.

1. Introduction

In the steelmaking industry, gas injection techniques have extensively been used in the refining processes. Molten metal contained in the reactor of the processes is agitated by injected gas through the gas-lift effect. It is possible to reduce refining time and save energy provided that an effective agitation method is developed. Methods of gas injection techniques can be classified into three types: bottom, top, and side blowing. Information on the bubble and liquid flow characteristics and mixing time in baths agitated by bottom and top gas injections is available owing to many efforts of researchers engaged in the steelmaking processes.⁵⁻⁷ Compared to top and bottom gas injection techniques,⁸⁻¹¹ information on those in a bath agitated by side gas injection is rather limited.

In the case of side gas injection, Themelis et al.,¹² Iguchi et al.,¹³ and Hashimoto et al.,¹⁴ reported that the bubble and liquid flow characteristics in a bath are very complicated because the flow is not axisymmetrical with respect to the vertical axis of the bath. Hiratsuka et al.,¹⁵ found that there appear several types of bath surface oscillations including a swirl motion in a bath agitated by side gas injection. The occurrence condition of the swirl motion is known to be different from that for bottom gas injection.¹⁶ Ternstedt et al.¹⁷ investigated mixing time in a bath agitated by side gas injection from a horizontal nozzle attached to the side wall of the vessel (see Fig. 1) and derived an empirical equation for the mixing time.

Particular attention is paid in this research series to mixing time in a bath agitated by horizontal gas injection through an L-shaped top lance. In a previous study¹⁸ we measured mixing time in the bath (see Fig. 2) and proposed an empirical equation for it. No attention was paid to the case that the swirl motion is absent. An empirical equation therefore is derived in this paper for mixing time in a bath.

![Fig. 1. Experimental apparatus for side gas injection in AOD process.](image1)

![Fig. 2. Experimental apparatus.](image2)
without the swirl motion and subsequently compared with that in the presence of the swirl motion.

2. Experimental Apparatus and Procedure

As noted, Fig. 2 shows a schematic of the experimental apparatus. Three test vessels were used: $D = 0.130$ m and $H = 0.600$ m, $D = 0.200$ m and $H = 0.400$ m, and $D = 0.300$ m and $H = 0.600$ m, where $D$ is the vessel diameter and $H$ is the vessel height. De-ionized water was filled to a predetermined depth, $H_L$. For example, the bath depth was chosen to be $H_L = 0.140$, 0.200, and 0.300 m for $D = 0.200$ m. The aspect ratio of the bath, $H_L/D$, was 0.7, 1.0, and 1.5. Air was injected into the bath through an L-shaped top lance. The inner diameter, $d_{in}$, and outer diameter, $d_{out}$, were $3.7 \times 10^{-3}$ m and $5.1 \times 10^{-3}$ m for $D = 0.130$ m and 0.300 m, and $4.1 \times 10^{-3}$ m and $6.4 \times 10^{-3}$ m for $D = 0.200$ m. The air flow rate, $Q_g$, was varied from $40 \times 10^{-6}$ m$^3$/s to $600 \times 10^{-6}$ m$^3$/s with a mass flow controller. The exit of the lance was placed on the centerline of the vessel. The depth from the bath surface to the lance exit, $H_{in}$, was varied so that the aspect ratio, $H_{in}/D$, fell between 0.2 and 0.5 for every vessel ($H_{in}/H_L = 0.133$–0.714).

Mixing time was determined from the history of the electrical conductivity of a liquid in the bath. An aqueous KCl solution was used as a tracer. It was charged from the top of the bath onto the bath surface. The electrical conductivity of the liquid was measured with an electrical conductivity sensor having a time constant of 0.25 s. The output voltage approaches a constant value, $V_F$, as time elapses, as shown in Fig. 3. Mixing time is defined as the period from the moment of tracer charge to the moment at which the electrical conductivity finally crosses 0.95 $V_F$ or 1.05 $V_F$. That is, the so-called 5% criterion was chosen in this study.

When air was injected into the bath, bubbles generated successively at the nozzle exit spread in the horizontal direction and then rose upwards in the bath. The bubble dispersion region was called a bubbling jet. The bubbling jet did not always rise monotonically in the bath. It sometimes rose in the bath while rotating around the vessel axis. The liquid near the bath also rotated chasing the bubbling jet. Such a rotation motion was named a swirl motion of the bubbling jet. Two types of swirl motions are known to appear: deep-water and shallow-water wave types. The radial dispersion of the bubbling jet was much greater in the former than in the latter, while the period of the former was approximately two times as large as that of the latter. The deep-water wave type of swirl motion is of practical importance because of its strong agitation power. The swirl motion of the shallow-water wave type was not observed under the experimental conditions chosen in this study.

3. Results and Discussion

3.1. Occurrence Condition of Swirl Motion

Figures 4 and 5 show the photographs of baths with and without swirl motion of the deep-water wave type, respectively. It is evident that the bath surface motion is more violent in Fig. 4 than in Fig. 5.

The occurrence condition of the deep-water wave type of swirl motion was specified as a function of gas flow rate, $Q_g$, and aspect ratio, $H_{in}/D$. Figures 6, 7, and 8 show bath surface oscillation maps for three vessel diameters. A swirl motion of the shallow-water wave type was not observed, as mentioned above. According to Hiratsuka et al., wave motions of the bath surface with gas injection through an L-shaped lance can be classified into eight patterns. The patterns except for the steady and intermittent swirl motions of the deep-water wave type were categorized into non-swirl motions in Figs. 6, 7, and 8. The occurrence regions of the steady and intermittent swirl motions can be predicted, as explained in the companion paper. Mixing time measurements were carried out in the absence of the deep-water wave type of swirl motion.
3.2. Measurement Results of Mixing Time and Derivation of an Empirical Equation for Mixing Time

Figures 9 through 11 show the relationship between the measured values of mixing time, $T_m$, and an empirical equation proposed by Ternstedt et al.\(^{17}\) for horizontal gas injection from a nozzle attached to the side wall. The equation was derived in the absence of swirl motion as:

$$T_m(g^{2/3}Q_g)^{0.2}/D = 86/Re^{0.2} \quad \ldots \quad (1)$$

$$Re = v_{sp}D/\nu_L \quad \ldots \quad (2)$$

$$v_{sp} = 4Q_g/(\pi D^3) \quad \ldots \quad (3)$$

where $g$ is the acceleration due to gravity, $Re$ is the Reynolds number, $v_{sp}$ is the superficial velocity of gas, and $\nu_L$ is the kinematic viscosity of liquid. Equation (1) is
rewritten in a dimensional form as:

\[ T_m = 32.9 \nu^{0.2} D^{1.2} Q_g^{-0.4} \] ....................... (4)

The measured value of mixing time, \( T_m \), decreased with gas flow rate, \( Q_g \), for every bath aspect ratio, \( H_L/D \), while it slightly increased with an increase in \( H_L/D \). The empirical equation, Eq. (4), significantly underestimated the mixing time, \( T_m \). That is, Eq. (4) yields a shorter mixing time value than the measured one under every experiment condition and it cannot explain the dependency of \( T_m \) on \( H_L/D \). This underestimation can be explained from the fact that the experiments of Ternstedt et al. were carried out for baths whose aspect ratio, \( H_L/D \), was smaller than unity and, as a result, a larger scale recirculating flow was induced by side wall gas injection than by L-shaped top lance gas injection.

However, further examination of Figs. 9 through 11 revealed that the presently obtained mixing time approaches that in a bath of the AOD process agitated by side gas injection with a decrease in the aspect ratio \( H_L/D \). Meanwhile, the mixing time is hardly dependent on the dimensionless nozzle position, \( H_{in}/H_L \), as shown, for example, for \( H_L/D = 0.7 \) in Fig. 12.

Subsequently, the measured values of \( T_m \) were compared with the following empirical equation derived for a bath agitated by gas injection through a J-shaped lance,\(^{19,20}\) as can be seen in Figs. 13 through 15.

\[ T_m(H_L/D)(g/D)^{1/2} = 4.21 \times 10^3 \mathrm{Re}^{-0.47} (H_{in}/H_L)^{0.7-1.34} H_L/D \] .......................................... (5)

This equation was obtained in the absence of a swirl motion of the deep-water wave type. Equation (5) is transformed into the following dimensional form.

\[ T_m = 1200 Q_g^{-0.47} D^{1.97} H_L^{-1} \nu^{0.47} \times (H_{in}/H_L)^{0.7-1.34} H_L/D \] .......................................... (6)

Equation (5) slightly overestimated the mixing time. The

**Fig. 11.** Relationship between mixing time and gas flow rate (\( D = 0.300 \) m).

**Fig. 12.** Relationship between mixing time and gas flow rate for different \( H_{in}/D \) values (\( D = 0.130 \) m).

**Fig. 13.** Comparison of measured mixing time values with Eq. (6) proposed by Takatsuka et al. (\( D = 0.130 \) m).

**Fig. 14.** Comparison of measured mixing time values with Eq. (6) proposed by Takatsuka et al. (\( D = 0.200 \) m).

**Fig. 15.** Comparison of measured mixing time values with Eq. (6) proposed by Takatsuka et al. (\( D = 0.300 \) m).
reason is that a greater scale recirculating flow is induced by L-shaped lance gas injection than by J-shaped lance gas injection, as schematically shown in Fig. 16. Bubbles generated by an L-shaped lance rise mainly near a radial position far away from the centerline of the bath. As a result, the scale of the recirculating flow induced by the gas-lift effect becomes large compared to the J-shaped lance whose nozzle exit is placed on the centerline of the bath. The effect of the recirculating flow scale on the mixing time was previously discussed by Joo and Guthrie\(^{21}\) for a bottom blown bath. According to them, in the case of the off-set agitation with bottom blowing, the mixing time is shortened as the nozzle is moved away from the center toward the half radius. When the nozzle is set closer to the side-wall, a bubbling jet rises along the side-wall because of the Coanda effect. This might cause a part of the buoyancy force of the bubbles to be lost by slippage,\(^{21}\) and the recirculating flow is weakened. As a result, the mixing time of the off-set agitation might be longer than that of the centered agitation.

Figures 9 through 15 collectively suggest that the deviation of the measured values of \(T_m\) from Eq. (5) is much smaller than that from Eq. (1). Accordingly, Eq. (5) was chosen for deriving an empirical equation for \(T_m\) in a bath agitated by gas injection through an L-shaped lance. The measured mixing time values were non-dimensionalized by operation parameters such as gas flow rate, \(Q_g\), and plotted in Fig. 17. The values were satisfactorily correlated by this arrangement method regardless of the bath aspect ratio, \(H_L/D\). The following empirical equation therefore was derived.

\[
T_m(H_L/D)(g/D)^{1/2}Re^{0.47} = 3.10 \times 10^3 (H_{in}/H_L)^{0.63-1.21} (H_L/D)
\]

\((D = 0.130–0.300 \, \text{m}, \, H_L/D = 0.7, \, 1.0, \, 1.5, \, H_{in}/D = 0.2–0.5, \, H_{in}/H_L = 0.133–0.714, \, Re = 372–4950)\) ...................... (7)

Figure 18 demonstrates that the measured values of \(T_m\) can be approximated by Eq. (7) within a scatter of ±60%. According to previous investigations on mixing time, this level of scatter is practically acceptable.

3.3. Comparison of Mixing Time Values Calculated from Empirical Equations for L-shaped and J-shaped Lances

As shown in the previous section, the empirical equation proposed for L-shaped lance gas injection gives a shorter mixing time value than that for J-shaped lance gas injection. Figure 19 compares the mixing time values calculated from the two equations, Eqs. (5) and (7). The difference between the two equations is insensitive to the dimensionless immersion depth, \(H_{in}/H_L\), and the aspect ratio, \(H_L/D\), under the present experimental conditions.
3.4. Comparison of Mixing Values in the Baths with and without Swirl Motion

Concerning bottom gas injection, mixing time is significantly shortened when a swirl motion of the deep-water wave type occurs. A preferable aspect ratio of the bath for the occurrence of the swirl motion ranges from about 0.3 to about unity. Such a swirl motion is very beneficial to the enhancement of the bath mixing efficiency, while it causes rotary sloshing on the bath surface. The sloshing enhances the erosion of the refractory of the vessel. According to this disadvantage, the swirl motion is not used in the steelmaking industry at present. In environmental engineering, however, the swirl motion becomes to be extensively used for wastewater treatments. If the erosion problem is solved, the usage of the swirl motion would be a promising method of shortening the mixing time in the steelmaking industry.

Considering these circumstances, it seems effective to compare the presently proposed empirical equation, Eq.

\[ T_m = \frac{1}{0.7} \left( \frac{H_d}{H_i} \right)^{0.7} \left( \frac{L}{D} \right)^{0.63} \left( \frac{d_{n1}}{D} \right)^{0.47} \]



with that derived in the presence of the swirl motion.\(^{18}\)

Figure 20 shows the mixing time values in the baths with and without the swirl motion. Gas injection was, of course, carried out using an L-shaped lance for \( D = 0.200 \) m, \( H_i/D = 0.7 \), and \( H_d/H_i = 0.3 \). The solid and broken lines denote empirical equations for the baths with and without swirl motion. It is interesting to note that the mixing time is shorter in the presence of the swirl motion, just in the case of bottom gas injection.

Mixing time, \( T_m \), is not always shorter in the presence of the swirl motion, as can be seen in Fig. 21. When the aspect ratio, \( H_d/D \), is around 0.7, \( T_m \) is shorter in the presence of the swirl motion for every dimensionless immersion depth, \( H_d/H_i \). On the other hand, \( T_m \) depends strongly on \( H_d/H_i \) in a complex manner. As \( H_d/H_i \) increases, the swirl motion gives longer mixing time.

3.5. Applicability of L-shaped Top Lance Gas Injection to the Steelmaking Process

Concerning the mixing of the current steelmaking processes, bottom and side gas injection systems are commonly used. Although these systems have high mixing intensity, some problems arise as mentioned in detail in the previous paper.\(^{22}\) First, the maintenance of a bottom nozzle or nozzles is one of the problems. The erosion of the bottom nozzle is severe especially under high gas flow rates. On the other hand, the weeping phenomenon occurs when the gas flow rate is relatively low. Here, weeping means that the molten steel descends the nozzle due to gravity. The same situations would be seen for the side nozzle gas injection. Second, a change in the configuration of the nozzle or nozzles is rather difficult.

The weeping phenomenon can be diminished and gas injection location can readily be varied by making use of an L-shaped top lance, although the erosion and oscillation of the top lance are still serious problems. Anyway, data on the flow characteristics and mixing time for L-shaped top lance gas injection are rather limited. Further investigation on this type of gas injection should be carried out in order to discuss the merits and demerits of the current bottom and side gas injection processes and the presently proposed process.

Fortunately, information on the mixing time obtained in this study is directly applicable to wastewater treatment because the erosion of the top lance is not serious in this engineering field.

4. Conclusions

(1) Mixing time measurements were carried out for a water bath agitated by horizontal gas injection through an L-shaped lance. Any kinds of swirl motions were not observed under the experimental conditions chosen in this study. The following empirical equation, Eq. (7), was proposed for mixing time. The measured values of mixing time were approximated Eq. (7) within a scatter of ±60%.

\[ T_m = C(T(H_d/D)(g/D)^{0.47} = 3.10 \times 10^3(H_d/H_i)^{0.65-1.21(H_d/D)} \]

(2) The L-shaped top lance gas injection gives a mixing time shorter than the J-shaped one. This is because a larger scale recirculating flow is induced in the bath when an L-shaped lance is used.

(3) The swirl motion of the deep-water wave type does not always gives a mixing time shorter than that in the absence of it, as can be seen in Fig. 21.

Nomenclature

- \( D \): vessel diameter
- \( d_{n1} \): inner nozzle diameter
- \( d_{n2} \): outer nozzle diameter
- \( g \): acceleration due to gravity
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