Swirl Motions Caused by Horizontal Gas Injection with an L-Shaped Lance

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Experimental investigations are carried out on the bath surface oscillations caused by horizontal air injection through an L-shaped lance into a cylindrical bath. Several types of bath surface oscillations are observed depending on the gas flow rate, the lance exit location, and so on. A bath surface oscillation map is drawn to identify the occurrence conditions of the oscillations. Particular attention is paid to the deep-water wave type swirl motion because of its practical importance. Empirical equations are newly proposed to describe the occurrence condition of the swirl motion. The measured values of the period and amplitude of the swirl motion compare favorably with their respective empirical equations proposed previously for bottom gas injection. [doi:10.2320/matertrans.M2010117]

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1. Introduction

Effective agitation of a molten metal bath is of essential importance in the steelmaking industry. The conventional mixing methods can be classified into three types: (1) gas injection, (2) electromagnetic agitation, and (3) mechanical agitation.¹,² Gas injection is considered to be the most economical and efficient method among these three agitation methods.

Conventionally used gas injection techniques are further categorized into three types: bottom gas injection through a single bottom nozzle or multi bottom nozzles, top gas injection through a lance, and a combined top and bottom gas injection.¹,² Concerning the bottom gas injection, the weeping phenomenon is one of serious problems encountered in practical applications.³ The weeping means that molten steel descends the nozzle due to gravity when the gas flow rate is low. This phenomenon is very dangerous and must be avoided. Fortunately, it never occurs in the case of top lance gas injection. The shortage of the top lance vertical gas injection, however, is the erosion of lance nozzle exit by floating bubbles once issued out downward through the nozzle. Therefore, horizontal gas injection by top lance has been used. Some problems however should happen in case of applying gas injection method to the steel refining processes. The most serious problem is the bath surface oscillations caused by impingement of bubbles onto the bath surface. Many types of bath surface oscillations are known to take place.⁴,⁵ The purpose of this study therefore is to make clear the occurrence conditions of the bath surface oscillations. Particular attention was paid to swirl motions of the bath surface. This is because these swirl motions are responsible for the erosion of refractory and the vessel oscillations. These occurrence conditions of the swirl motion were investigated in the case of horizontal gas injection using an L-shaped lance comparing with bottom gas injection.

2. Experiment

Figure 1 shows a schematic of the experimental apparatus.

Air was injected from an L-shaped lance, where $D$ is the vessel diameter, $H_L$ is the bath depth, $H_b$ is the immersion depth of the lance, and $r$ is the horizontal displacement of the plume eye appearing on the bath surface. The inner and outer diameters of the lance, $d_{in}$ and $d_{ou}$, were 3.7 mm and 5.1 mm for $D = 160$ mm, 4.1 mm and 6.4 mm for $D = 200$ mm, and 3.8 mm and 5.1 mm for $D = 300$ mm, respectively. The exit of the lance was placed on the centerline of the vessel and its stem was located at $r = R/2$. The radial distance and the vessel radius were denoted by $r$ and $R$, respectively. The flow rate of air, $Q_g$, was adjusted with a mass flow controller. The bath surface oscillations were observed by eye inspection and with a high-speed camera.

In the real processes there exists a slag layer on the surface of the molten metal. The bath surface oscillation is likely to be suppressed by the slag layer because the kinematic viscosity of slag is usually higher than that of molten metal. Accordingly, the bath surface oscillations in the presence of slag would be different from those observed in this study. Investigation on this subject must be left for a future study.

3. Experimental Results and Discussion

3.1 Classification of bath surface oscillations

The bath surface oscillations were previously classified into seven types.⁶ As a detailed explanation on them can be
seen in the previous paper, the essence of them will be reproduced in the following.

3.1.1 Steady swirl motion of the deep-water wave type

Swirl motions caused by horizontal gas injection can be classified into two categories depending on the dimensionless lance immersion depth, \( H_n / D \), where \( H_n \) is the lance immersion depth and \( D \) is the vessel diameter.\(^5\) The swirl motion of the deep-water wave type appeared for \( H_n / D \) greater than about 0.3. The buoyancy forces acting on bubbles generated in the bath are effectively used to circulate the liquid in the bath unlike the swirl motion of the shallow-water wave type explained later.\(^6\)–\(^8\) Accordingly, the amplitude of this type of swirl motion was much greater than that of the shallow-water wave type. The direction of the swirl motion is governed by the Coriolis force. Provided that the vessel is large enough, the direction is counter-clockwise on the northern hemisphere of the earth. The vessels used in this study are not so large, that the direction is not definite because the effect of the Coriolis force is negligibly small.\(^6\)–\(^8\) This type of swirl motion is useful for the mixing of fluids in many engineering fields.\(^9\)–\(^13\)

3.1.2 Intermittent swirl motion of the deep-water wave type

The swirl motion of the deep-water wave type sometimes stopped for a while and then started under a certain blowing condition. These events were repeated nearly periodically.

3.1.3 Intermittent swirl motion of the shallow-water wave type

When the lance immersion depth, \( H_n \), was smaller than about 0.3\( D \), the so-called blowout of injected gas took place and, as a result, the amplitude of the bath surface oscillation became very small. The radial displacement of the bubbling jet was small as well, as schematically shown in Fig. 2.

3.1.4 Steady lateral oscillation

The bath oscillated in the lateral direction under a certain condition, as seen in Fig. 3.

3.1.5 Intermittent longitudinal oscillation

The bath oscillated intermittently in the longitudinal direction, as indicated in Fig. 4.

3.1.6 Random fluctuation

The bath fluctuated randomly in all directions, as can be seen in Fig. 5.

3.1.7 Impingement of bubbling jet onto the side wall of the vessel

Bubbles generated in the bath reached the side wall of the vessel when the gas flow rate was raised above a certain value (see Fig. 6). This phenomenon is not expected in practical use because of severe erosion of sidewall and of vessel oscillations.

3.1.8 Without fluctuations

No definite fluctuation was observed when the gas flow rate was very low.

3.2 Occurrence condition of the swirl motion of the deep-water wave type

It is of practical importance to make clear the occurrence condition of the swirl motion of the deep-water wave type. Figures 7 through 9 show the bath surface oscillation maps for the vessel diameters of 160 mm, 200 mm, and 300 mm, respectively. The lines indicated by (I), (II), (III), and (IV) denote the boundary of the occurrence region of the swirl motion of the deep-water wave type for bottom gas injection.\(^5\) Empirical equations describing the four sub-boundaries are expressed as follows.\(^5\)
3.2.1 Sub-boundary (I)

\[ H_n/D = 0.19F_{\text{rmD}}^{-1/20} \]  
\[ F_{\text{rmD}} = Q_g^2/(gD^3) \]

where \( F_{\text{rmD}} \) is the modified Froude number and \( g \) is the acceleration due to gravity.

3.2.2 Sub-boundary (II)

\[ H_n/D = (1.0 + 0.3 \log We)^{1/2} \]  
\[ We = \rho_L Q_g^2/(\sigma D^3) \]

where \( We \) is the Weber number, \( \rho_L \) is the density of liquid, and \( \sigma \) is the surface tension.

3.2.3 Sub-boundary (III)

\[ H_n/D = 1.09 \]

3.2.4 Sub-boundary (IV)

\[ H_n/D = 3.4[\rho_L Q_g^2/(\sigma g)]^{0.3}/(Dd_d^{0.5}) \]

where \( \rho_L \) is the density of gas.

The physical meaning of the four sub-boundaries can be summarized as follows. The sub-boundary (I) indicates the limit between the deep-water wave and shallow-water wave types. The sub-boundary (II) shows the condition that a swirl motion appears when the pressure fluctuation at the bath surface caused by impingement of a bubbling jet exceeds a certain critical value. The sub-boundary (III) denotes the condition that a swirl motion is suppressed as the radial displacement of the bubbling jet at the bath surface is too large. The sub-boundary (IV) shows the condition that the bubbling jet penetrates too high above the bath surface and hence the swirl motion cannot occur.

The occurrence region of swirl motion of the deep-water wave type for horizontal gas injection became very narrow compared with the bottom gas injection. Accordingly, the empirical equations for the bottom gas injection are not applicable to horizontal gas injection.

3.3 Derivation of empirical equations describing the boundary of the occurrence region of the swirl motion of the deep-water wave type

3.3.1 Sub-boundary (I)

Some of bubbles generated at the lance exit migrated in the downward direction due to spreading of a bubbling jet and then rose upwards after reaching a certain vertical position below the lance exit. This fact suggests that the bubbles behave as if the lance exit were lowered. Equation (1) therefore was modified to give

\[ (H_n + k_1 D)/D = 0.19F_{\text{rmD}}^{-1/20} \]  

where \( k_1 \) is a fitting parameter. The value of \( k_1 \) was chosen so that eq. (7) best fits the observed sub-boundary (I) for the three vessels. As shown later in Figs. 10–12, the coefficient, \( k_1 \), was found to be 0.15 and eq. (7) reduces to

\[ (H_n + 0.15 D)/D = 0.19F_{\text{rmD}}^{-1/20} \]  

3.3.2 Sub-boundary (II)

In a similar manner to the discussion on the sub-boundary (I), eq. (3) was modified as follows:

\[ (H_n + 0.15 D)/D = (1.0 + 0.3 \log We)^{1/2} \]
Swirl Motions Caused by Horizontal Gas Injection with an L-Shaped Lance

3.3.3 Sub-boundary (III)

Equation (5) was originally derived by assuming that the swirl motion ceases when the diameter of the plume eye on the bath surface exceeds a certain value. This value is known to be \(0.61D\) for bottom gas injection. The same criterion was used for horizontal gas injection.

\[
D_{\text{jet}}/D = 0.61 \quad (10)
\]

\[
D_{\text{jet}} = k_2L_{\text{at}} + 4b_u \quad (11)
\]

\[
L_{\text{at}} = 3.7d_{\text{at}}F_{\text{r}}^{1/3} \quad (12)
\]

\[
b_u = 0.14H_u \quad (13)
\]

\[
F_{\text{r}} = (\rho_g Q_g^2)/(\rho_g d_{\text{at}}^5) \quad (14)
\]

where \(D_{\text{jet}}\) is the plume eye diameter, \(L_{\text{at}}\) is the horizontal migration distance of bubbles, \(b_u\) is the half-value radius of water flow velocity distribution in the bubbling jet, \(F_{\text{r}}\) is another kind of modified Froude number, and \(k_2\) is a fitting parameter.

The same procedure as that for \(k_1\) was chosen for determining \(k_2\).

Combining eqs. (10) through (13) yields

\[
H_u/D = 1.09 - 3.7k_2d_{\text{at}}F_{\text{r}}^{1/3}/D. \quad (15)
\]

The fitting parameter, \(k_2\), was found to be

\[
k_2 = 2.0. \quad (16)
\]

Observation of the bubble dispersion in the bath suggests that this value is reasonable. Accordingly, substitution of eq. (16) into eq. (15) yields

\[
H_u/D = 1.09 - 7.4d_{\text{at}}F_{\text{r}}^{1/3}/D. \quad (17)
\]

3.4 Amplitude of the swirl motion of the deep-water wave type

As a first step, the following empirical equations derived originally for bottom gas injection were compared with the data on the amplitude of the swirl motion of the deep-water wave type.

\[
A/D = 0.224\{Re^{1/2}(H_uQ_u)/(D^{7/2}/g^{1/2})\}^{0.3} \quad (18)
\]

\[
0.02 < \{Re^{1/2}(H_uQ_u)/(D^{7/2}/g^{1/2})\} \leq 0.45
\]

\[
= 0.143\{Re^{1/2}(H_uQ_u)/(D^{7/2}/g^{1/2})\}^{-0.25} \quad (19)
\]

\[
0.45 < \{Re^{1/2}(H_uQ_u)/(D^{7/2}/g^{1/2})\} < 7
\]

\[
Re = (Q_g^2/g)^{2/5}(g/D)^{1/2}/\nu L \quad (20)
\]

where \(Re\) is the Reynolds number.

Figures 13 through 15 show that the measured values can be satisfactorily approximated by eq. (18) within a scatter of \(\pm 50\%\).

3.5 Period of the swirl motion of the deep-water wave type

The swirl motion of the deep-water wave type is very similar to the rotary sloshing caused by external oscillation of a cylindrical vessel containing partially filled liquid.

The period of the rotary sloshing, \(T_c\), can be theoretically given by
\[ T_s = 2\pi\left(\frac{\varepsilon_1 g}{D} \cdot \tanh\left(\frac{2\varepsilon_1 H_n}{D}\right)\right)^{0.5} \quad (21) \]

where \( \varepsilon_1 = 1.84 \) is the first zero of the Bessel function, \( J_1 \). Figures 16 through 18 demonstrate that eq. (21) is valid also for the horizontal gas injection.

4. Conclusions

Experimental observation was made on the bath surface oscillations appearing under horizontal gas injection through an L-shaped lance. Particular attention was paid to the swirl motion of the deep-water wave type because of its practical importance. The main findings obtained in this study can be summarized as follows.

(1) The bath surface oscillations were classified into seven categories and their occurrence regimes were indicated on the bath surface oscillation map.
(2) Empirical equations, eqs. (8), (9), and (17), were derived for describing the boundary of the occurrence region of the swirl motion of the deep-water wave type.
(3) The amplitude of the swirl motion of the deep-water wave type was predicted by an empirical equation, eq. (18), derived originally for bottom gas injection.
(4) The period of the swirl motion of the deep-water wave type agreed favorably with an equation, eq. (21), theoretically derived for the rotary sloshing in a partially filled cylindrical vessel.
REFERENCES