Swinging Motion of Bath Surface Induced by Side Gas Injection

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(Received on March 29, 2004; accepted in final form on August 25, 2004)

Cold model experiments were carried out to understand a swinging motion of the bath in the AOD process. Water and air were used as the working fluids. A water bath contained in a cylindrical vessel was agitated by side gas injection using an L-shaped lance. Under a certain blowing condition the surface of the bath swung in the vertical direction like a liquid column oscillating in a U-shaped tube. The preferable occurrence condition of this swinging motion was correlated with the size of a plume eye on the bath surface and the vessel diameter. Empirical equations were proposed for the period and amplitude of the swinging motion.

KEY WORDS: steelmaking; refining; AOD process; gas injection; bath oscillation; wastewater treatment.

1. Introduction

A swirl motion of a cylindrical bath is induced by bottom gas injection under a certain blowing condition.1–6) This swirl motion resembles the rotary sloshing caused by oscillating a cylindrical bath in the horizontal or vertical direction.7,8) In addition, a swinging motion similar to that of a liquid column contained in a U-shaped tube takes place when nozzles of more than two are placed, for example, on the same diameter of the bottom of the vessel.1,9) Such swirl and swinging motions occur preferentially for an aspect ratio, $A_s$, ranging from approximately 0.2 to approximately unity and induce violent wave motions. Spattering, splashing, and spitting are closely associated with the wave motions. Accordingly, the swirl and swinging motions of the bath are not welcome to the steelmaking industry. Many investigations have been carried out on the occurrence conditions, period, and amplitude of the two motions and mixing time in the presence of the two motions. At present, much information is available on these subjects.1–6,9,10)

A swinging motion similar to that appearing in a U-shaped tube is also observed in a bath agitated by side gas injection. Unfortunately, information on this swinging motion is very limited,11) although the information is useful for wastewater treatment using injection of an ozone and air mixture12) as well as the AOD process.13,14)

In this study water model experiments were carried out to clarify the details of the swinging motion caused by side gas injection. Air was injected into a cylindrical bath in the horizontal direction towards the centerline of the bath with an L-shaped top lance placed near the sidewall of the vessel. The swinging motion was observed with a high-speed video camera.

2. Experiment

Figure 1 shows a schematic diagram of the experimental apparatus. The test vessel made of transparent acrylic resin had an inner diameter, $D$, of 0.15, 0.20, and 0.30 m. De-ionized water was filled in each vessel at a predetermined depth. Air was injected into the water bath in the horizontal direction through a single-hole nozzle attached to the tip of an L-shaped top lance. The temperatures of the water and air were 20°C. Although the pressure of air in the nozzle is not measured, this does not cause any trouble because the relationship between the gas flow rate at the nozzle exit and the scale of the mass flow controller is predetermined. The stem of the lance was placed in contact with the side wall of the vessel. The length of the horizontal part of the lance was denoted by $L_n$. The inner nozzle diameter, $d_{iw}$, was set to be $2.0 \times 10^{-1}$ m. The nozzle height, $H_n$, was measured from the bottom of the vessel and set to be $0.1D$, $0.5D$ and $1.0D$. The distance from the nozzle exit to the bath surface, $H_s - H_n$, was divided by the vessel diameter, $D$. This ratio, $(H_s - H_n)/D$, was termed the aspect ratio, $A_s$, and varied from 0 to 1.0 in each vessel. The shape of the nozzle was fixed in this study. The effects of the nozzle configuration on the penetration behavior of bubbling jet must be left for a future study.

The injected gas disintegrated into many bubbles of different diameters and thus a bubble dispersion region was formed in the bath, as schematically shown in Fig. 2. The bubble size at the nozzle exit ranged from approximately 4 mm to 15 mm under the present experimental conditions. The bubble velocity and liquid velocity are not measured. The bubble dispersion region was called the bubbling jet. The penetration depth of the jet in the horizontal direction
was denoted by \( L_{H} \). The top view of the bubble dispersion region at the bath surface, called the plume eye, was taken by a high-speed video camera. In the presence of the swinging motion, the plume eye widened in the swinging direction and shortened in the injecting direction. The origin of the coordinate system was placed on the side wall of the vessel. The width of the plume eye in the \( x \) direction was denoted by \( 4b_{ax} \) and that in the \( y \) direction was denoted by \( 4b_{ay} \), where \( b_{ax} \) and \( b_{ay} \) are the half-value radii of the gas holdup distributions in the \( x \) and \( y \) directions, respectively.\(^{11} \)

The period, \( T_{s} \), and amplitude, \( A \), of the swinging motion of the bath were determined by observing the swinging motions over 50 periods. The amplitude, \( A \), is defined as a half of the difference between the maximum and minimum heights of the bath surface on the side wall of the vessel.

3. Experimental Results and Discussion

3.1. Parameters Describing the Horizontal Penetration Depth and Plume Eye on the Bath Surface

3.1.1. Horizontal Penetration Depth of Bubbling Jet

The size of a plume eye on the bath surface is closely associated with the occurrence of a swinging motion of a bath.\(^{15} \) Information on the horizontal penetration depth, \( L_{H} \), is available in the absence of the swinging motion.\(^{11,16} \)

\[
L_{H} = 3.7 \frac{d_{mi}}{Fr_{m}^{1/3}} \quad \text{(1)}
\]

where \( d_{mi} \) is the inner nozzle diameter and \( Fr_{m} \) is a modified Froude number defined as

\[
Fr_{m} = \rho_{g} Q_{g}^{2} (\rho_{g} g d_{mi}^{5}) \quad \text{(2)}
\]

where \( \rho_{g} \) and \( \rho_{l} \) are the densities of gas and liquid, respectively, \( Q_{g} \) is the gas flow rate, and \( g \) is the acceleration due to gravity.

The values of \( L_{H} \) measured in this study are shown together with Eq. (1) in Fig. 3. Equation (1), indicated by a broken line, underestimated the presently measured values, and accordingly, Eq. (1) was modified as follows:

\[
L_{H} = 4.5 \frac{d_{mi}}{Fr_{m}^{1/3}} \quad \text{(3)}
\]

Equation (3) is indicated by a solid line. The measured values can be approximated by Eq. (3) within a scatter of \( \pm 30\% \) (correlation coefficient, \( Cr_{H} = 0.868 \)). The correlation coefficients for other quantities are similar to this value.

The measured values of \( L_{H} \) seem to be slightly dependent on the vessel diameter, \( D \). However, the scattering of the data are not small, and accordingly, quantitative evaluation of the effect of \( D \) is difficult at present.

3.1.2. Size of Plume Eye

The values of \( b_{ax} \) and \( b_{ay} \) determined by measuring the size of a plume eye on the bath surface are shown in Figs. 4 and 5, respectively. A broken line in each figure represents an empirical equation proposed originally for side gas injection in the absence of the swinging motion.\(^{11} \)

\[
b_{ax} / L_{H} = 0.147(z/L_{H})^{0.55} (0.5 < z/L_{H} < 3) \quad \text{.........(4)}
\]

\[
b_{ay} / L_{H} = 0.39(z/L_{H})^{0.88} (0.5 < z/L_{H} < 3) \quad \text{.........(5)}
\]
Equation (4) underestimates the width of the plume eye in the x direction, while Eq. (5) overestimates that in the y direction. These equations were modified to fit the presently measured values.

\[ \frac{b_{ax}}{L_H} = 0.19(z/L_H)^{0.55} \quad \ldots \quad (7) \]

\[ \frac{b_{ay}}{L_H} = 0.27(z/L_H)^{0.088} \quad \ldots \quad (8) \]

Equations (7) and (8), drawn by a solid line in each figure, can approximate the measured values within a scatter of \( \pm 40\% \). Such a degree of scattering is acceptable in this kind of measurement. The difference between Eqs. (4) and (7) and that between Eqs. (5) and (8) are attributable to the hydrodynamic drag acting on bubbles in the swinging direction. Just as in the case of \( L_n \), the effects of the vessel diameter, \( D \), on \( b_{ax} \) and \( b_{ay} \) must be left for a future study.

### 3.2. Occurrence Condition of Swinging Motion

The region in which a swinging motion occurs is shown in Fig. 6 for three vessels of different diameters as a function of the aspect ratio, \( A_s \), and the gas flow rate, \( Q_g \). The occurrence of a swinging motion was judged by eye inspection. The horizontal length of the L-shaped lance, \( L_n \), is 0.04 m and the non-dimensional nozzle position, \( H_n/D \), is 0.5. The minimum and maximum aspect ratios are hardly dependent on the vessel diameter, \( D \). The occurrence region, however, shifts in the right direction as the vessel diameter increases. The volume of the liquid in the bath increases with an increase in the vessel diameter, \( D \), and hence, more input energy is required for causing the swinging motion.

The data indicating the boundary of the occurrence region for \( L_n=0.04 \) m are re-plotted against a dimensionless parameter, \( (L_n+L_H)/D \), in Fig. 7, where \( (L_n+L_H) \) indicates the farthest horizontal bubble position away from the stem of the lance. Equation (3) was used for evaluating \( L_H \). Measurements were carried out over an aspect ratio of 0.1 to 1.0 and a gas flow rate from 20 to 640 cm\(^3\)/s. A swinging motion does not occur in the region enclosed with these...
limits and the boundary of the occurrence region of the swinging motion. The boundary of the occurrence region can be correlated by this arrangement method. The same is true for $L_n/H_n = 0.01$ m and $0.02$ m, as demonstrated in Figs. 8 and 9. In addition, the occurrence regions for the three $L_n$ values agree well with one another. Concerning $L_n/H_n = 0.08$ m, this arrangement method loses its validity (see Fig. 10), because a bubbling jet is localized very close to the side-wall of the vessel located at $y/D$ due partly to the Coanda effect. This effect arises when a jet is formed beside a solid wall. In Fig. 10 some of the measured values of $(L_n + L_H)/D$ are greater than unity. The reason is that Eq. (3) is used for calculating $L_H$ instead of measured values.

These results collectively suggest that the occurrence condition of the swinging motion can be correlated as a function of the aspect ratio, $A_s$, and $(L_n + L_H)/D$ when $L_n/D$ falls between 0.033 and 0.267.

### 3.3. Period of Swinging Motion

The swinging motion observed in this study resembles the radial oscillation mode of the rotary sloshing caused by external oscillation of the vessel. The period, $T_s$, of the radial oscillation mode was given by Kimura and Ohashi. The presently measured values of the period are shown in Fig. 11. The solid line denotes the period of the rotary sloshing. The period was hardly affected by the aspect ratio, $A_s$, gas flow rate, $Q_g$, and nozzle height, $H_n$. It agreed with the period of the fundamental radial oscillation mode of the rotary sloshing for an aspect ratio greater than approximately 0.2. Consequently, the period of the swinging motion can be expressed by the following empirical equation within a scatter of ±7% under the present experimental conditions.

$$T_s = 3.3(D/g)^{1/2}$$

![Fig. 8. Correlation of occurrence region of swinging motion $(L_n=0.02\text{ m})$.](image)

![Fig. 9. Correlation of occurrence region of swinging motion $(L_n=0.01\text{ m})$.](image)

![Fig. 10. Correlation of occurrence region of swinging motion $(L_n=0.08\text{ m})$.](image)

![Fig. 11. Period of swinging motion.](image)
measurements were carried out for an elevated nozzle position. In other words, the present data are not influenced by the bottom wall of the vessel.

3.4. Amplitude of Swinging Motion

Figure 12 shows the measured values of the amplitude, $A$, of the swinging motion for $L_n = 0.01$ m against gas flow rate, $Q_g$. The amplitude, $A$, increases with $Q_g$. The dependency of $A$ on the vessel diameter, $D$, is not clear. We assume that $A$ is proportional to the height of the plume eye, $H_{elB}$. According to the previous studies on a bottom blown bubbling jet, the velocity of liquid flow induced by a bubbling jet is approximated by

$$\frac{U_{elB}}{H_{elB}} = k_1 \left( \frac{g Q_g}{2} \right)^{1/5}$$............................................................(10)

where $k_1$ is a constant. This equation is assumed to be valid also for a bubbling jet generated by side blowing. The height of the plume eye, $H_{elB}$, is given by

$$H_{elB} = k_2 \left( \frac{Q_g}{g} \right)^{1/2}$$............................................................(11)

Substitution of Eq. (10) into Eq. (11) yields

$$H_{elB} = k_3 \left( \frac{Q_g}{g} \right)^{1/5}$$............................................................(12)

where $k_2 = k_1^2/2$.

We further assume that the amplitude, $A$, is a function of $H_{elB}$ and the vessel diameter, $D$, and thus $A$ is expressed by

$$\frac{A}{D} = k_4 \left( \frac{Q_g}{g} \right)^{1/5}$$............................................................(13)

where $k_4$ and $m$ are constants. Figure 13 shows the measured values of $A/D$ against the non-dimensional length, $(Q_g^2 / g)^{1/5}/D$. The measured values of $A/D$ for all $L_n$ values can be successfully approximated by Eq. (13). Accordingly, the following equation was derived.

$$\frac{A}{D} = 1.1 \left[ (Q_g^2 / g)^{1/5} / D \right]^{1.2}$$............................................................(14)

Equation (14) is indicated by a solid line in Fig. 13. The measured values can be approximated by Eq. (14) within a scatter of ±50%. Such a degree of scattering is acceptable in this kind of measurement.

4. Conclusions

The main findings obtained in this study can be summarized as follows:

1. The horizontal penetration depth of a side blown bubbling jet can be predicted by the following empirical equation proposed in this study.

$$L_H = 4.5 \frac{d_i}{F_{rm}^{1/3}}$$............................................................(3)

2. The half-value radii of bubble dispersion region in a plume eye, $b_{ax}$ and $b_{ay}$, can be predicted by

$$b_{ax} / L_H = 0.19 (z/L_H)^{0.55}$$............................................................(7)

$$b_{ay} / L_H = 0.27 (z/L_H)^{0.088}$$............................................................(8)

3. The occurrence condition of a swinging motion induced by a side blown bubbling jet can be correlated as a function of the aspect ratio, $A_s$, and a dimensionless parameter, $(L_n + H_n)/D$ for $L_n/D = 0.033 – 0.267$, as shown in Figs. 7 through 9.

4. The period, $T_s$, and amplitude, $A$, of the swinging motion of the bath surface are approximated by

$$T_s = 3.3 (D/g)^{1/2}$$............................................................(9)

$$\frac{A}{D} = 1.1 \left[ (Q_g^2 / g)^{1/5} / D \right]^{1.2}$$............................................................(14)

Nomenclature

- $A$: Amplitude of swinging motion (m)
- $A_s$: Aspect ratio = $(H_L - H_n)/D$ (–)
- $4b_{ax}$, $4b_{ay}$: Longitudinal and lateral sizes of plume eye on the bath surface (m)
- $d_i$: Inner nozzle diameter (m)
- $F_{rm}$: Modified Froude number (–)
- $g$: Acceleration due to gravity (m/s²)
- $H$: Vessel height (m)
- $H_n$: Nozzle height measured from vessel bottom (m)
- $L_{elB}$: Horizontal penetration depth (m)

Fig. 12. Amplitude of swinging motion ($L_n = 0.01$ m).

Fig. 13. Correlation of amplitude of swinging motion.
\( L_n \) : Horizontal length of L-shaped lance (m)

\( Q_g \) : Gas flow rate (m\(^3\)/s)

\( T_s \) : Period of swinging motion (s)

\( z \) : \( H_L - H_0 \) (m)

\( \rho_g, \rho_L \) : Densities of gas and liquid, respectively (kg/m\(^3\))

REFERENCES