Prediction of the Period of Swirl Motion Appearing in Gas Injection Processes at High Temperatures

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A swirl motion induced by gas injection through a bottom nozzle has high mixing ability and useful for the mixing of a molten steel bath in the refining processes. As one of the fundamental characteristics of the swirl motion, the period is mentioned in this study. A semi-empirical equation is proposed for the period of swirl motion by referring to the rotary sloshing appearing in a cylindrical vessel oscillated in the vertical or the horizontal direction.

Key Words: steel refining, high-temperature process, environmental problem, agitation, molten steel jet

1. INTRODUCTION

Bottom gas injection processes are extensively used in the steelmaking industries¹⁻³). Bubbles generated successively at the nozzle exit in a bath rise upward due to the buoyancy force acting on themselves. The bubble dispersion region thus formed above the nozzle is called the bubbling jet. The bubbles do not always rise straight upward. Under specific conditions the bubbling jet swirls around the vessel axis like the well-known rotary sloshing^{4,5}). The bath would be highly mixed in the presence of the swirl motion of the bubbling jet⁶).

The present authors are trying to develop a novel process using such a swirl motion to save energy and hence to decrease CO₂ gas emission. The purpose of this study is to understand the period of swirl motion induced by gas injection through a centered bottom nozzle.

Two kinds of swirl motions are known to be induced in a bath contained in a cylindrical vessel by injecting gas into the bath⁵), as shown in Fig.1.

The shallow-water wave type and deep-water wave type swirl motions appear depending on the aspect ratio of the bath. The critical aspect ratio is approximately 0.3. The latter has a high mixing ability, and accordingly, it finds wide applications such as snow melting⁷) and wastewater treatments⁸).

As mentioned above, the swirl motions are very similar to the rotary sloshing, which is induced in a bath contained in a cylindrical vessel subjected to external oscillations in the

horizontal or the vertical direction. The period of swirl motion was found to be approximated by an analytical equation derived for the period of rotary sloshing⁵). However, a clear difference can be seen between the period of swirl motion and that of rotary sloshing, although the difference is small. In this study discussion was given on the causes of this difference and a semi-empirical equation was proposed.

2. FLOW FIELD IN THE PRESENCE OF SWIRL MOTION OF BUBBLING JET

Previous studies on the swirl motion of a bubbling jet⁹) revealed

Fig.1 Swirl motions induced by bottom gas injection

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that when the bubbling jet rotates, for example, clockwise, the liquid outside the bubbling jet rotates counterclockwise so as to satisfy the conservation law of angular momentum. When the aspect ratio of the bath, H_L/D , is relatively small, the upper part of the liquid rotating counterclockwise reaches the bath surface. This motion can be clearly seen by putting small amount of silicone oil on the water bath surface. The region where the liquid moves counterclockwise on the bath surface becomes narrow as the aspect ratio, H_L/D , increases.

One more interesting feature of the flow field mentioned here is that bubbles of many sizes are contained in the bath. Large bubbles are successively generated at the nozzle exit. These bubbles are disintegrated into smaller bubbles having diameters over a wide range. In addition, many small bubbles are entrapped into the bath from the bath surface near the side wall of the vessel due to violent wave motions.

A total volume, V_g , of the large bubbles rising from the nozzle towards the bath surface can be predicted, as the bubble rising velocity, u_B , is known³⁾.

$$V_g = Q_g H_L / u_B \quad (1)$$

where Q_g is the gas flow rate and H_L is the initial bath depth before gas injection. In the real situation the bath depth becomes greater than H_L due to the existence of bubbles in the bath. This increment is neglected in this study because the total volume of gas, V_g , is much smaller than the volume of liquid, V_L , in the bath and the effect of bath depth on the period of swirl motion of the deep-water wave type is very small. It is difficult at the present stage to precisely predict the total volume of small bubbles entrapped from the bath surface into the bath. The small bubbles therefore are not mentioned in the following analysis.

The apparent density, ρ_{app} , of the mixture of liquid and gas in the bath is expressed by

$$\rho_{app} = (\rho_g V_g + \rho_L V_L) / (V_g + V_L) \quad (2)$$

where ρ_g is the density of gas and ρ_L is the density of liquid. By introducing an apparent acceleration due to gravity, g_{app} , the balance of forces acting on the bath is expressed by

$$\rho_g V_g g + \rho_L V_L g - \rho_L V_g g = \rho_{app} (V_g + V_L) g_{app} \quad (3)$$

where g is the acceleration due to gravity.

Combination of Eqs.(2) and (3) yields

$$g_{app} = [1 - \rho_L V_g / (\rho_g V_g + \rho_L V_L)] g \quad (4)$$

As $\rho_g V_g$ is much smaller than $\rho_L V_L$, Eq.(4) reduces to

$$g_{app} = (1 - V_g / V_L) g \quad (5)$$

3. EXPERIMENTAL APPARATUS

Figure 2 shows a schematic diagram of the experimental apparatus. The cylindrical test vessel made of transparent acrylic resin had an inner diameter, D , of 80mm to 390mm. The inner diameter of the nozzle, d_n , was varied from 1.0mm to

Fig.2 Experimental apparatus

Rotary sloshing

Fig.3 Rotary sloshing in a cylindrical vessel

5.0mm. Water and mercury were used as the working fluids. The kinematic viscosity of water is nearly equal to that of molten steel. Air was injected into the test vessel with a compressor. The period of swirl motion was measured with a high-speed video camera and by eye inspection. The experimental results obtained with an LDV will be reported elsewhere.

4. DERIVATION OF EQUATION FOR THE PERIOD OF SWIRL MOTION

4.1 PERIOD OF ROTARY SLOSHING

Figure 3 shows a schematic illustration of the rotary sloshing appearing in a vessel containing partially filled liquid in it. Much information is available on the rotary sloshing. The period of the lowest mode of the rotary sloshing is expressed by

$$T_s = 2\pi [(3.68g/D)\tanh(3.68H_L/D)]^{-1/2} \quad (6)$$

A semi-empirical equation will be derived for the period of swirl motion of the deep-water wave type by referring to Eq.(6).

4.2 PERIOD OF SWIRL MOTION OF BUBBLING JET

Fig.4 Comparison of measured values of the period of swirl motion in water bath with Eq.(12) and period for rotary sloshing

Figures 4 and 5 compare the measured values of the period of swirl motion with Eq.(6) for centered gas injection through a bottom nozzle¹⁰⁾. Equation (6) was denoted by a solid line in each figure. The deep-water wave type swirl motion appeared for an aspect ratio between about 0.3 and about unity. The difference between the measured values and E.(6) is small, but a definite difference can be seen. The value calculated from Eq.(6) decreased with a decrease in the aspect ratio, while the measured value remained almost unchanged in the region between $H_L/D = 0.3$ and 1.0. We assume that such a difference is caused by the two fluid flow phenomena mentioned in the preceding section.

Equation (6) is modified as follows:

$$T_s = 2\pi[(3.68g_{app}/D_{app})\tanh(3.68H_{Lapp}/D_{app})]^{-1/2} \quad (7)$$

As mentioned earlier, it is difficult to precisely evaluate the total volume of bubbles existing in the bath, we further assume that g_{app} is constant under the present experimental conditions and H_{Lapp} is equal to H_L . Under these assumptions Eq.(7) reduces to

$$1/T_s = 1/(2\pi)[(3.68g_{app}/D_{app})\tanh(3.68H_L/D_{app})]^{1/2} \quad (8)$$

Multiplying the both sides of Eq.(8) by $(D/g)^{1/2}$ yields

$$(D/g)^{1/2}/T_s = [1/(2\pi)][(g_{app}/g)(D/D_{app})]^{1/2} \times [3.68\tanh\{3.68(H_L/D)(D/D_{app})\}]^{1/2} \quad (9)$$

In the following section expressions for g_{app}/g and D/D_{app} will be determined based on the experimental results of the present authors shown in Figs.4 and 5. It is reasonable to assume that $D/D_{app} = 1.0$ for $H_L/D = 1.0$, and accordingly, we have

$$(D/g)^{1/2}/T_s = 0.28 \quad (H_L/D = 1.0) \quad (10)$$

Substitution of Eq.(10) into Eq.(9) gives

$$g_{app}/g = (0.918)^2 \quad (11)$$

Combination of Eq.(11) and Eq.(9) yields

$$(D/g)^{1/2}/T_s = [0.918/(2\pi)](D/D_{app})^{1/2} \times [3.68\tanh\{3.68(H_L/D)(D/D_{app})\}]^{1/2} \quad (12)$$

The measured values of $(D/g)^{1/2}/T_s$ are assumed to be nearly constant in the region from H_L/D of about 0.3 to about unity.

Fig.5 Comparison of measured values of the period of swirl motion in silicone and mercury baths with Eq.(12) and period for rotary sloshing

Substitution of $(D/g)^{1/2}/T_s = 0.28$ and $H_L/D = 0.3$ into Eq.(12) gives

$$D/D_{app} = 1.17 \quad (13)$$

As one of the simplest expressions, the following linear relationship was chosen for D/D_{app} .

$$D/D_{app} = 1.25 - 0.25H_L/D \quad (14)$$

The period of swirl motion of the deep-water wave type for any aspect ratio can be estimated by substituting Eq.(14) into Eq.(12). Equation (12) is adequate for predicting the period of swirl motion of the deep-water wave type, as shown in Figs.4 and 5.

4.3 APPLICABILITY OF Eq.(12) TO SWIRL MOTION OF LIQUID JET

The period of a swirl motion caused by liquid jet injection¹¹⁾ is known to be favorably approximated by the period of rotary sloshing, Eq.(6)¹²⁾. This is because the inertial force of the injected liquid is directly used for driving the liquid in the bath. Accordingly, the bath is much more strongly agitated by the liquid jet than by gas injection. This fact suggests that the apparent diameter in Eq.(12), D_{app} , is nearly the same as the vessel diameter D ($D/D_{app} \approx 1$), regardless of the aspect ratio. In addition, the volume of bubbles contained in the bath is much smaller than that in the bath with gas injection. This fact suggests that $g_{app}/g \approx 1$ in Eq.(12).

4. CONCLUSIONS

The following semi-empirical equation was proposed for the period of swirl motion of the deep-water wave type appearing in the baths with bottom gas injection.

$$(D/g)^{1/2}/T_s = [0.918/(2\pi)](D/D_{app})^{1/2} \times [3.68\tanh\{3.68(H_L/D)(D/D_{app})\}]^{1/2} \quad (12)$$

The diameter ratio in Eq.(12) is given by

$$D/D_{app} = 1.25 - 0.25H_L/D \quad (14)$$

NOMENCLATURE

D	vessel diameter
D_{app}	apparent vessel diameter
d_n	inner diameter of nozzle
g	acceleration due to gravity
g_{app}	apparent acceleration due to gravity
H_L	bath depth
Q_g	gas flow rate
T_s	period of swirl motion
u_B	bubble rising velocity
V_g	total volume of bubbles in the bath
V_L	volume of liquid in the bath
ρ_{app}	apparent density
ρ_g	density of gas
ρ_L	density of liquid

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