Swirl Motion of a Mercury Jet Appearing in a Cylindrical Vessel in Transient Period

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1. Introduction

A swirl motion of a bottom blown bath agitated by a liquid jet appears under specific injection conditions. 1) – 8) There are two types of swirl motions depending on the aspect ratio of the bath: shallow-water and deep-water wave types. 9) The aspect ratio is defined as the ratio of the bath depth, \( H \), to the vessel diameter, \( D \). The shallow-water wave type occurs when the aspect ratio is smaller than about 0.3 and the jet swirls around the vessel axis with small deflection. On the other hand, the deep-water wave type occurs in the aspect ratio range from about 0.3 to about 1.7. The jet departs significantly from the vessel axis while swirling around the vessel axis. The bath is highly agitated in the presence of this type of swirl motion.

We have been trying to apply the deep-water wave type swirl motion to a variety of environmental and engineering processes such as snow melting, 9) wastewater treatment, 10) dioxin treatment, sludge treatment, 11) rare earth leaching, 12) and cadmium reduction from guts. The occurrence condition can be correlated in terms of the aspect ratio, \( \mu = \frac{H}{D} \), and the modified Rossby number, \( \text{Ro}_\text{m} \), defined as

\[
\text{Ro}_\text{m} = \frac{Q_L^2}{(g D^3 L/2)}
\]

where \( Q_L \) is the liquid flow rate, \( g \) is the acceleration due to gravity, \( d_\text{tan} \) is the inner diameter of the nozzle. In addition, empirical equations for the period, amplitude, starting time, and damping time of the swirl motion of the bath were proposed. The amplitude was defined as a half of the difference between the highest and lowest water surface positions on the side wall of the vessel. The period was defined as the time required for a jet to swirl around the vessel axis once. However, it is not clear whether the information thus obtained from water model experiments is useful for predicting the swirl motion of a molten metal bath or not.

Unfortunately, pumps capable of driving molten metal of a temperature of higher than 1 500°C are not available. We therefore previously proposed a system shown schematically in Fig. 1. The potential energy of molten metal is used for driving the molten metal itself. 3) The liquid in the bath is effectively agitated by a liquid jet in the presence of the swirl motion of the jet. Further explanation of the system can be seen in the previous paper. 3)

The characteristics of the deep-water wave type swirl motion of a mercury bath agitated by a mercury jet were experimentally investigated in this cold model study. Mercury of a predetermined volume was introduced into a transparent, cylindrical glass vessel through a centered bottom nozzle. The potential energy of the mercury was used for introducing it into the vessel. The mercury jet became to swirl around the vessel axis under specific injection conditions. As a result, the swirl motion of the bath was induced. The occurrence region, period, and amplitude of the swirl motion were determined and compared with those obtained from water model experiments.

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic of the experimental apparatus. The test vessel was made of transparent glass and had an inner diameter, \( D \), of 80 mm, an outer diameter of 96 mm, and a height of 280 mm. The inner diameter of the nozzle, \( d_\text{tan} \), was 5 mm. Mercury was contained in the storage vessel placed above the test vessel. Also, mercury was initially filled in the test vessel to a predetermined depth (\( H = H_{\text{in}} \)). The position of the storage vessel can be varied to adjust the injection velocity of the mercury into the test vessel. The physical properties of mercury are listed in Table 1 together with those of water, silicone oil, and molten steel. The motion of mercury in the test vessel was observed with a high-speed video camera. The occurrence region, period and amplitude of the swirl motion of the mercury bath were determined from the images recorded on the camera. The bath depth, \( H_{\text{in}} \), was determined as a mean of the highest and lowest water surface positions on the side wall of the vessel.
3. Experimental Results and Discussion

3.1. Photographs of Mercury Jet and Its Swirl Motion

Figure 3 shows a mercury jet generated in the test vessel. The initial aspect ratio of the bath, \( H_L/D \), was 0.25. The mercury flow rate, \( Q_L \), was 54.9 cm\(^3\)/s and the modified Rossby number, \( \text{Ro}_m \), was 0.0241. The injection velocity, \( v_n \), is defined as follows:

\[
v_n = \frac{4Q_L}{(\pi d_{\text{inj}}^2)} \tag{2}
\]

The injection velocity was 280 cm/s. The jet generated in the bath rose straight upward above the initial bath surface. After a while, the jet became to oscillate in the radial direction and finally rotated around the vessel axis with the mercury in the bath, as shown in Fig. 4.

3.2. Occurrence Region

The critical bath depths indicating the initiation and cessation of the swirl motion were determined from the video images. Figure 5 shows the occurrence region of the swirl motion in terms of the aspect ratio, \( H_L/D \), and the modified Rossby number, \( \text{Ro}_m \). Empirical equations proposed originally for the boundary of the occurrence region of the swirl motion of a water bath in the transient period\(^6\) also were drawn in the figure. These equations are expressed as follows:

(1) Sub-boundary (I)

\[
H_L/D = 0.0131 \text{Ro}_m^{-1/2} \tag{3}
\]

(2) Sub-boundary (II)

\[
H_L/D = 7.06 \text{Ro}_m^{1/3} \tag{4}
\]

(3) Sub-boundary (III)

\[
H_L/D = 1.86 \tag{5}
\]

(4) Sub-boundary (IV)

\[
H_L/D = 26 \text{Ro}_m \tag{6}
\]

\[
H_L/D = 4.33 \text{Ro}_m^{1/2} \tag{7}
\]

The solid circles denote the boundary of the occurrence region of the swirl motion of a water bath. Namely, the swirl motion of a water bath appeared in the region enclosed with the solid circles. The aspect ratio of the initial bath depth was 0.30. The occurrence region of the swirl motion of the mercury bath was denoted by a straight line parallel to the vertical axis. Although it should be noted that the initial aspect ratios are slightly different from each other for the two systems, the occurrence region of the swirl motion of the mercury bath is nearly in agreement with that of the water bath. This fact means that the occurrence region of the swirl motion of the mercury bath also is correlated by the aspect ratio, \( H_L/D \), and the modified Rossby number, \( \text{Ro}_m \). Consequently, the physical properties of liquid do not affect the occurrence region of the swirl motion, as previously discussed based on experiments using silicone oils listed in Table 1.\(^{11}\)

Table 1. Physical properties of liquids.

|                | Water | Silicone oil 1cSt | Silicone oil 10cSt | Mercury | N-pentane | Molten steel |
|----------------|-------|------------------|--------------------|---------|-----------|-------------|
| Temperature (K)| 298   | 298              | 298                | 298     | 298       | 1973        |
| Density \(\rho_c (\text{kg/m}^3)\) | 997   | 818              | 935                | 13546   | 630       | 7210        |
| Surface tension \(\sigma (\text{mN/m})\) | 72.7  | 52.7             | 52.7               | 476     | 57.8      | 1000        |
| Kinematic viscosity \(\nu (\text{mm}^2/\text{s})\) | 0.891 | 1.0              | 10                 | 0.110   | 0.37      | 0.929       |

Fig. 2. Experimental apparatus.

Fig. 3. Photograph of mercury jet.

Fig. 4. Photograph of swirl motion of mercury bath.

Fig. 5. Boundary of occurrence region of swirl motion of mercury bath in the transient period.
3.3. Period of Swirl Motion

The period and amplitude of swirl motion also were obtained from the video images. Figure 6 shows the period, $T_s$, of swirl motion against the aspect ratio, $H_l/D$. The solid line in the figure denotes the period of rotary sloshing of a bath contained in a cylindrical vessel which is oscillated externally in the vertical or horizontal direction. The period of rotary sloshing can be expressed by

$$T_s = 2\pi/\omega_1 \quad \text{..........................(8)}$$

$$\omega_1 = [(2g\varepsilon_1/D) \cdot \tanh(2\varepsilon_1 H_l/D)]^{1/2} \quad \text{..........................(9)}$$

where $\varepsilon_1$ (=1.84) is the first zero of the Bessel function, $J_1'(\varepsilon)$. The variable on the vertical axis was derived from Eqs. (8) and (9). The period of the swirl motion of mercury bath was satisfactorily predicted by the period of rotary sloshing, just as in the case of swirling water baths.

3.4. Amplitude of Swirl Motion

The amplitude of swirl motion at any moment was determined by dividing the difference between the highest and the lowest water levels on the side wall of the vessel at that moment by 2. Figure 7 shows the measured values of the amplitude thus determined. The measured dimensionless value of amplitude, $A/D$, was in the same order of magnitude as that in a water bath of constant aspect ratio. Further experiments are needed to derive an empirical equation for the amplitude in a bath of varying depth.

3.5. Applicability of Information on Swirl Motions of Water and Mercury Baths to Molten Steel Bath

The above-mentioned experimental results revealed that the occurrence region and period of the deep-water type swirl motion of a bath are not affected by the physical properties of liquid. This fact suggests that the swirl motion of a molten steel bath can be generated using the potential energy of the molten steel and it will be effectively applicable to continuous refining processes. In addition, these processes can save energy because the potential energy of molten steel is used for mixing the molten steel itself.

4. Conclusions

Experimental investigation was carried out on the occurrence condition, period, and amplitude of the deep-water wave type swirl motion of a mercury bath. The results were predicted by empirical and analytical equations proposed previously for those of a swirling water bath. The swirl motion therefore is not affected by the physical properties of liquid. This fact suggests that the deep-water wave type swirl motion of a molten steel bath will be effectively applicable to continuous steel refining processes.

Nomenclature

$A$: Amplitude of swirl motion
$D$: Vessel diameter
$d_{ina}$: Inner diameter of nozzle
$g$: Acceleration due to gravity
$H_l$: Bath depth
$L$: Liquid flow rate
$Ro_m$: Modified Rossby number
$T_s$: Period of swirl motion

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