Proposal of a Novel Agitation Method using Swirl Motion of Molten Metal Jet

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When a liquid was injected into a cylindrical bath of the same liquid through a centered bottom nozzle, a liquid jet was formed above the nozzle. The jet did not always rise straight upward, but exhibited a swirl motion under a certain condition. The bath was strongly agitated in the presence of the swirl motion. A molten metal jet also can be generated using a potential energy difference between two vessels containing the molten metal. The occurrence of the swirl motion is therefore useful for the development of a novel refining process. As a first step of this research series, the critical condition for the occurrence of the swirl motion, the swirl period and the amplitude were investigated in this study. Empirical equations for the period and amplitude were proposed.

KEY WORDS: steelmaking; refining; swirl motion; Rossby number; jet; sloshing; oscillation.

1. Introduction

Development of innovative agitation techniques have long been desired to highly promote metallurgical reactions and save energy in the refining processes. Three types of agitation methods are currently used: gas injection,1–7) mechanical stirring,8–12) and electromagnetic agitation.13–17) At present, gas injection is most widely used because of its easy handling, relatively low cost, and high agitation efficiency. As an effective method of gas injection, the authors recently have proposed a novel agitation method using the swirl motion of a bubbling jet.18–22) Although this method cannot find its application in the steelmaking industries yet, it is becoming to be used in other engineering fields such as snow melting in cold countries21) and treatment of organic waste water.22) The snow melting, for example, was highly promoted in the presence of the swirl motion of a bubbling jet.21

The swirl motion is known to appear as the upward molten metal flow induced by rising bubbles oscillates the bath surface and excites wave motions of preferable frequencies. The original driving force for the swirl motion of a bubbling jet therefore is the buoyancy force acting on rising bubbles. As a result, it takes relatively long time for the bubbling jet to exhibit the swirl motion after the start of gas injection. This fact suggests that the start-up time of the swirl motion would be extremely shortened by directly injecting molten metal into a molten metal bath of the same compositions from a bottom nozzle in place of injecting gas into the molten metal bath.

Such a swirl motion of a molten metal jet formed above the nozzle is beneficial for the development of a novel, continuous refining process, as schematically shown in Fig. 1. Molten metal is injected through a pipe nozzle connected to the bottom of the cylindrical vessel using the potential energy difference between the two vessels. The swirl motion of

Fig. 1. Schematic of a proposed continuous refining process.
the molten metal jet would appear under a certain injection condition, and, as a result, the metallurgical reactions relevant to refining are expected to be highly promoted. The molten metal after the refining is sent to the next process through a drainage hole (or holes) settled on the bottom of the vessel. The most pronounced advantage of this process is that it would be an energy-saving process because the potential energy difference between the liquid levels in the two reactors is effectively used without supplying additional energy.

Investigations on the swirl motion of a liquid jet are limited compared to those on the swirl motion of a bubbling jet. The focus of Madarame’s report is on the analysis of the oscillation modes of the surface of a water bath caused by a bottom blowing water jet. The characteristics of the swirl motion of the water jet are not described in detail in their report. In this study, model experiments were carried out on the critical condition for the occurrence of the swirl motion of a water jet formed in a cylindrical bath and the basic characteristics of the swirl motion.

2. Experimental Apparatus and Procedure

Figure 2 shows a schematic diagram of the experimental apparatus. The cylindrical test vessel was made of acrylic resin. Water was supplied from a centric, single bottom nozzle into the vessel, drawn from four drainage nozzles settled on the bottom of the vessel, and circulated with a pump. The bath depth was denoted by \( H \). The water flow rate, \( Q \), was varied from 0 to \( 750 \times 10^{-3} \) m\(^3\)/s using a frequency inverter equipped with the pump to control the rotation speed of the impeller of the pump. The density, \( \rho \), the kinematic viscosity, \( \nu \), and the surface tension, \( \sigma \), of the water were 996 kg/m\(^3\), 0.891 mm\(^2\)/s, and 72.7 mN/m, respectively at 298 K. The test vessel was enclosed with another vessel with a rectangular cross-section made of transparent acrylic resin. The clearance between the rectangular vessel and the cylindrical vessel was filled with water to avoid the distortion of video images of a swirling water jet observed from the side of the vessel.

Figure 3 shows the details of the test vessel. The inner diameter of the vessel, \( D \), the diameter of the circle on which four drainage nozzles are located, \( D_o \), the height of the vessel, \( H \), the inner diameter of the entrance nozzle, \( d_{ent} \), the inner diameter of the drainage nozzles, \( d_{dno} \), are listed in Table 1. The aspect ratio, \( H/L \), was varied from 0 to 4.

The occurrence of the swirl motion of a water jet was observed with a digital video camera and by eye inspection. The period and amplitude of the swirl motion were determined mainly based on the video images. The measurements were repeated three times under every experimental condition.

3. Results and Discussion

3.1. Classification of Swirl Motion of Water Jet

Two types of swirl motions of water jets were observed, as shown in Figs. 4 and 5. One is called the shallow-water wave type and known to be influenced by the bottom wall of the vessel. The water jet classified in this type rotat-
ed around the vessel axis in the central part of the bath. This type of swirl motion appeared for an aspect ratio smaller than about 0.3. The other is called the deep-water wave type. This type of swirl motion did not receive any effect of the bottom wall of the vessel and rotated along the side wall of the vessel. It appeared for an aspect ratio of greater than approximately 0.3. When the water flow rate was highly increased, the top of the swirling water jet behaved as if it were a fountain. The fountain rotated in synchronize with the rotation of the bath, as shown in Fig. 5(b). It became evident that many small bubbles are entrapped into the bath in the presence of the swirl motion of the deep-water wave type.

These two types of swirl motions resemble the rotary sloshing caused by forced oscillation of a cylindrical vessel containing liquid in it, and, for convenience, are named the first kind of swirl motion.

According to the previous studies on bubbling jets, bubbles generated at the nozzle exit rose swirling along the side wall of the vessel due to the Coanda effect when the aspect ratio was greater than about 2.0. This type of swirl motion, called the second kind of swirl motion, was not observed under the experimental conditions considered. Therefore, only the first kind of swirl motion will be mentioned in the subsequent sections.

3.2. Condition Describing the Occurrence of Swirl Motion of Water Jet

3.2.1. Derivation of Dimensionless Number

Figure 6 shows the boundary of the region in which swirl motion of a water jet of the deep-water wave type appears for \( D=0.200 \) m. The swirl motion appeared in the region surrounded by plots for each nozzle diameter, \( d_{\text{nen}} \).

The boundary shifted in the right direction with an increase in \( d_{\text{nen}} \). This is because the inertial force of the water jet, described later in Eq. (1), decreases with an increase in \( d_{\text{nen}} \), and accordingly, higher water flow rate is required to induce the swirl motion of the jet. The minimum aspect ratio of the boundary was approximately 0.1 regardless of the nozzle diameter, \( d_{\text{nen}} \). The upper boundary shifted upward almost linearly with the water flow rate before showing the minimum value of about 0.1 and then shifted upward, although the lower boundary for the swirl motion of a bubbling jet remained approximately 0.3. As already shown in Fig. 5(b), a liquid jet formed a fountain on the bath surface. The liquid falling from the fountain seems partly associated with the difference between the lower
boundaries of water and bubbling jets.

Figure 7 shows the critical conditions for the occurrence of the swirl motion of a water jet for three different vessel diameters. The nozzle diameter, $d_{\text{in}}$, was fixed to be 0.015 m. The boundary indicating the critical condition shifted in the right direction as the bath diameter, $D$, increased. This is because more input energy is required for a larger bath to maintain the swirl motion.

The aforementioned results suggest that the inertial force of a water jet and the centrifugal force acting on the rotating water mainly govern the flow field in the bath. A dimensionless number composed of the inertial force and the centrifugal force is known as the Rossby number, $Ro$. Accordingly, a modified Rossby number will be proposed in this study to correlate the critical condition for the occurrence of the swirl motion.

The inertial force of a water jet at the nozzle exit, $F_i$, is expressed by

$$F_i = \dot{m}U_i = \frac{4\rho_l Q_i^2}{\pi d_{\text{in}}^2} \quad \text{..........................(1)}$$

where $\dot{m}$ is the mass flow rate of the water jet, $U_i$ is the mean velocity of the water jet at the nozzle exit, and $\rho_l$ is the density of liquid. On the other hand, it is difficult to precisely evaluate the centrifugal force of the bath, $F_c$. We assume that $F_c$ is approximated by

$$F_c = \frac{m\omega^2}{2} \quad \text{..........................(2)}$$

where $m$ is the mass of water swirling in the bath, $\omega$ ($=2\pi/T_s$) is the angular frequency of the swirl motion of the water jet. The mass, $m$, was further assumed to be $\rho_l D^3$. Equation (2) is therefore rewritten by

$$F_c = \frac{2\pi^2 \rho_l D^4}{T_s^2} \quad \text{..........................(3)}$$

At a glance, it seems more reasonable to choose $m = \pi \rho_l H_l D^2/4$ instead of $m = \rho_l D^3$. The former relationship was found to give less accurate results than the latter chosen in this paper.

In Figs. 11 and 12 shown later, $T_s$ can be correlated by the following equation.

$$(D/\beta)^{3/2}/T_s = k \quad \text{..........................(4)}$$

where $g$ is the acceleration due to gravity and $k$ is a constant. Combination of Eqs. (3) and (4) yields

$$F_i = 2\pi^2 \rho_l g D^2 k \quad \text{..........................(5)}$$

The following modified Rossby number, $Ro_m$, was chosen from the division of Eq. (1) by Eq. (5).

$$Ro_m = \frac{Q_i^2}{g d_{\text{in}}^2 D^3} \quad \text{..........................(6)}$$

Figure 8 shows the boundary of the region in which the swirl motion of the deep-water wave type appears for $D=0.200$ m against the modified Rossby number, $Ro_m$. The boundary can be satisfactorily correlated by this arrangement method.

Figure 9 shows the relationship between the critical aspect ratio $H_l/D$ indicating the boundary of the swirl motion of a water jet and the modified Rossby number, $Ro_m$, for all experimental results. The boundary for the swirl motion of the deep-water wave type can be described as a function of the modified Rossby number, as shown in Fig. 9(a). The swirl motion of the shallow-water wave type also was correlated by this arrangement method, as shown in Fig. 9(b). The maximum aspect ratio for the appearance of the swirl motion of the deep-water wave type was approximately 1.7, while it was nearly 1.0 for the swirl motion of a bubbling jet.

3.2.2. Applicability of the Present Correlation Method to Previous Results

Madarame et al.\(^{23}\) reported the region in which the swirl motion of the deep-water wave type appeared. Figure 10 shows that their data also can be satisfactorily correlated by the presently proposed method. Madarame et al. drained the water in the bath from the outlets settled on the lower part of the side wall of the vessel. This drainage system is much different from that shown in Fig. 3. Accordingly, the drainage system does not have a significant effect on the occurrence of the swirl motion as long as the drainage holes are located near the bottom of the vessel.

3.2.3. Discussion on the Cessation of Swirl Motion

According to the previous study on the critical condition
for the cessation of the swirl motion of a bubbling jet, the swirl motion of the deep-water wave type ceased when the radial dispersion of the bubbling jet occupied a certain critical area on the bath surface. If this is valid for the cessation of the swirl motion of a liquid jet, the critical radial extent of the liquid jet would be equal to that of the bubbling jet. The radial extent can be represented by the half-value radius, \( b_{uwj} \) of the radial distribution of the axial mean velocity component of liquid flow. The half-value radii of a water jet and a bubbling jet are expressed as follows:

\[
\begin{align*}
    b_{uwj} &= 0.09z & \text{(Water jet)} \\
    b_{ubj} &= 0.14z & \text{(Bubbling jet)}
\end{align*}
\]

where \( z \) is the vertical distance from the nozzle exit. The half-value radii under the critical condition, \( b_{uwj} \) and \( b_{ubj} \), are expressed by

\[
\begin{align*}
    b_{uwj}/H_{Lwj} &= 0.09 \\
    b_{ubj}/H_{Lbj} &= 0.14
\end{align*}
\]

where \( H_{Lwj} \) and \( H_{Lbj} \) are the critical bath depth for the water jet and bubbling jet, respectively. The ratio of \( b_{uwj} \) to \( b_{ubj} \) is given by

\[
\frac{b_{uwj}}{b_{ubj}} = \frac{9H_{Lwj}}{14H_{Lbj}}
\]

Substitution of Eq. (12) into Eq. (11) yields

\[
\frac{b_{uwj}}{b_{ubj}} = \frac{9 \times 1.7}{14} = 0.91
\]

This ratio is approximately unity, and accordingly, suggests the adequacy of the assumption that the critical bath depth for the cessation of the swirl motion of the deep-water wave type is closely associated with the radial dispersion of a water jet on the bath surface.

3.3. Swirl Period

The difference between the shallow-water wave type and deep-water wave type of swirl motions can be clearly recognized in the swirl period. It is known for the swirl motions of bubbling jets that the swirl period is approximately equal to the frequency of the rotary sloshing appearing in a cylindrical vessel subjected to external forced oscillations. The frequency of the sloshing, \( f_{s,i,j} \), is given by

\[
f_{s,i,j} = \frac{1}{2\pi} \left( 2g \epsilon_{i,j} (H_i / D) \cdot \tanh(2\epsilon_{i,j}H_i/D) \right)^{1/2}
\]

where \( \epsilon_{i,j} \) is the \( j \)th zero of Bessel function \( J_i(t) \). Equation (14) reduces to Eq. (15), when \( f_{s,i,j} \) is transformed into the swirl period, \( T_{s,i,j} \), where \( i \) and \( j \) indicate the numbers of the circumferential and radial partition lines of the wave in the sloshing.

\[
T_{s,i,j} = 2\pi \left( 2g \epsilon_{i,j} / D \cdot \tanh(2\epsilon_{i,j}H_i/D) \right)^{1/2}
\]

Figures 11 and 12 show the swirl period nondimensionalized in the same manner as that for a bubbling jet. The round plate with partly shaded region (hatching) described in each figure schematically shows the configuration of the wave in the sloshing. The shaded region denotes the water surface higher than the initial water level, while the white region denotes the water surface lower than the initial water level. The numerical values, 1 and 2, in Fig. 11, indicate the
sloshing modes corresponding to \( i \) and \( j \) in Eq. (15). Namely, \( \varepsilon_{1,1} \) in Eq. (15) is 5.331. The swirl period of the shallow-water wave type was satisfactorily approximated by the period of the sloshing mode (1, 2), as shown in Fig. 11. On the other hand, the swirl period of the deep-water wave type shown in Fig. 12 agreed well with the period of the sloshing mode (1, 1), where \( \varepsilon_{1,1} \) is 1.841.

### 3.4. Amplitude of the Swirl Motion of Water Jet

Figures 13 and 14 show the amplitude of the swirl motion of a water jet, \( A \), of the deep-water wave type. The amplitude, \( A \), was defined as a half of the peak to peak value and measured with a digital video camera. In every figure \( A \) increased monotonically with an increase in the water flow rate. Figure 15 demonstrates that the amplitude, \( A \), can also be correlated as a function of the modified Rossby number, \( R_{om} \).

\[
\frac{A}{D} = 3.5 R_{om}^{0.5}
\]

Equation (16) can approximate the measured values of the amplitude within a scatter of \( \pm 40\% \). Such a scattering is acceptable in this kind of measurement.
3.5. Applicability of the Swirl Motion to Steelmaking Processes

Concerning bubbling jets, both the shallow-water wave type and deep-water wave type of swirl motions appeared in a molten metal bath agitated by bottom gas injection.\(^{11}\) The characteristics of the bubbling jet in the molten metal bath were predicted by those obtained from the water model experiments. As the mechanism of the occurrence of the swirl motion of a liquid jet is the same as that of a bubbling jet, the presently obtained findings would be useful for a molten metal bath agitated by a molten metal jet. Confirmation however should be made using low-temperature molten metals such as mercury and Wood’s metal.

4. Conclusions

Water model experiments were carried out to investigate the critical condition for the occurrence of the swirl motion of a liquid jet in a cylindrical bath. Also, measurements were made of the period and amplitude of the swirl motion. Main findings obtained in this study can be summarized as follows.

(1) The aspect ratio indicating the boundary of the region in which the swirl motion appeared was correlated in terms of the newly proposed modified Rossby number, \( R_{\text{m}} \). Equation (16) was proposed for the prediction of the amplitude.

(2) The periods of the swirl motions of the deep-water wave type and shallow-water wave type were approximated by Eq. (15).

(3) The amplitude of the swirl motion of the deep-water wave type was correlated as a function of the modified Rossby number, \( R_{\text{m}} \). Equation (16) was proposed for the prediction of the amplitude.

Nomenclature

\[
\begin{align*}
A & : \text{Amplitude of swirl motion} \quad (\text{m}) \\
b_h & : \text{Half-value radius} \quad (\text{m}) \\
d_{\text{en}} & : \text{Inner diameter of entrance nozzle} \quad (\text{m}) \\
d_{\text{dn}} & : \text{Inner diameter of drainage nozzle} \quad (\text{m}) \\
D_b & : \text{Diameter of a circle on which drainage nozzles are located} \quad (\text{m}) \\
f & : \text{Frequency of the rotary sloshing} \quad (\text{Hz}) \\
F_c & : \text{Centrifugal force} \quad (\text{N}) \\
F_i & : \text{Inertial force} \quad (\text{N}) \\
g & : \text{Gravitational acceleration} \quad (\text{m}/\text{s}^2) \\
H & : \text{Vessel height} \quad (\text{m}) \\
H_b & : \text{Bath depth} \quad (\text{m}) \\
k & : \text{Coefficient} \quad (-) \\
m & : \text{Mass of swirling liquid} \quad (\text{kg}) \\
m & : \text{Mass flow rate} \quad (\text{kg/s}) \\
Q_L & : \text{Water flow rate} \quad (\text{m}^3/\text{s}) \\
R_{\text{m}} & : \text{Modified Rossby number} \quad (-) \\
T_s & : \text{Swirl period} \quad (\text{s}) \\
U & : \text{Mean velocity at nozzle exit} \quad (\text{m/s}) \\
z & : \text{Vertical distance from the nozzle exit} \quad (\text{m}) \\

\end{align*}
\]

Greek letters

\[
\begin{align*}
\nu & : \text{Kinematic viscosity of water} \quad (\text{mm}^2/\text{s}) \\
\rho & : \text{Density of water} \quad (\text{kg/m}^3) \\
\sigma & : \text{Surface tension of water} \quad (\text{mN/m}) \\
\omega & : \text{Angular frequency of swirl motion} \quad (\text{rad/s}) \\

\end{align*}
\]

Subscripts

\[
\begin{align*}
i & : \text{Number of circumferential partition lines of wave in sloshing} \\
b_j & : \text{Bubbling jet} \\
w_j & : \text{Water jet} \\

\end{align*}
\]

REFERENCES