Water-model Experiment on Melting Powder Trapping by Vortex in the Continuous Casting Mold

Norifumi KASAI1) and Manabu IGUCHI2)

2) Division of Materials Science and Engineering, Graduate School of Engineering, Hokkaido University, North 13 West 8, Kitaku, Sapporo 060-8628 Japan.

Water-model experiments have been carried out to understand the behavior of mold powder trapping phenomena by vortex in continuous casting mold. The following findings are obtained.

1) Mold powder trapping by the vortex occurs irregularly near the immersion nozzle. It occurs only in the wake of the immersion nozzle.
2) As for the occurrence frequency ratio of the vortex, the maximum value appears in the water flow rate regime ranging from 61.4 to 70.2 L/min. This regime is supposed to have a lose relationship with water flow velocity change near the immersion nozzle.
3) An empirical equation is proposed for the length of the molten mold powder entrapped by the vortex.

KEY WORDS: continuous casting; mold powder; trapping; vortex; water-model.

1. Introduction

In recent years, as for the mechanism of melted mold powder trapping in the high-speed continuous slab casting mold, water-model experiments have been extensively carried out, and much information1–3) is available. For example, critical velocities for mold powder trapping caused by several mechanisms were derived by Yoshida et al.4) The critical velocity data are useful for investigating plans for the prevention of the mold powder trapping in the real continuous casting mold. Unfortunately, the most influential mechanism of mold powder trapping is not clarified yet. Further investigation is requested for the clarification of the mechanism.

The Karman’s vortices formed downstream of the immersion nozzle are said to be one of the causes for mold powder trapping.5) They are induced by uneven flow appearing almost periodically in the mold.6) When the mold powder trapping is caused by the Karman’s vortices, it also must appear almost periodically downstream of the immersion nozzle.

No information is available on the relationship between the occurrence frequency of mold powder trapping and the shedding frequency of Karman’s vortex streets. In addition, effects of the operation factors such as the depth of the immersion nozzle and the nozzle port angle on the mold powder trapping are not clear at the present stage.

In this study we focused on the effect of molten steel flow on the mold powder trapping occurring near the immersion nozzle due to Karman’s vortex. In particular, the occurrence frequency of mold powder trapping and the penetration depth of the vortex just before trapping were investigated in detail.

2. Experimental Apparatus and Procedure

The experiment apparatus used for the water-model experiments is schematically shown in Fig. 1. The model mold is a 1/2.5 scale of the actual continuous casting ma-
chine. Water flow rate in the immersion nozzle was controlled with a sliding gate by using the output signals of the flow meter and the pressure sensor. The water surface in the mold was kept at a constant level.

Measurement positions of water flow velocity in the model mold bath are shown in Fig. 2, and the experimental conditions are listed in Table 1. The water flow rate, $Q_w$, nozzle port angle, $\theta_n$, and the depth of the immersion nozzle, $d$, were varied over a wide range. The following Froude number similitude was chosen to plan model experiments for the actual continuous casting machine.

$$Fr = \frac{u_0}{(gD_{ni})^{1/2}}$$...............................(1)

where $Fr$ is the Froude number, $u_0$ is the average velocity of water flow at one of the two nozzle ports, $g$ is the acceleration due gravity, and $D_{ni}$ is the cross-sectional area equivalent diameter of the port.

Liquid paraffin was mainly used as a model liquid for melted mold powder. This model liquid was colored in red by adding phenol red to make it visible. Silicone oils in red color also were used under limited experimental conditions. The physical properties of these liquids were measured after addition of the phenol red. The initial thickness of the mold powder layer was 1 cm.

A propeller type velocimeter of a diameter of 0.3 cm was used to measure the water flow velocity around the immersion nozzle. The measurement time was 10 min under every experimental condition. The occurrence frequency and the penetration depth of vortexes filled with the model mold powder liquid were measured with a video camera and by eye inspection. The effects of the water flow velocity on these quantities were clarified. The reason for the choice of the measurement positions shown in Fig. 2 will be explained in a later section.

### Table 1. Experimental conditions of water model.

<table>
<thead>
<tr>
<th>Physical properties of mold powder</th>
<th>Liquid paraffin</th>
<th>SI Oil A</th>
<th>SI Oil B</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\rho = 0.76\text{ g/cm}^3$</td>
<td>$\rho = 0.85\text{ g/cm}^3$</td>
<td>$\rho = 0.92\text{ g/cm}^3$</td>
</tr>
<tr>
<td></td>
<td>$\eta = 64.0\text{ cp}$</td>
<td>$\eta = 45.8\text{ cp}$</td>
<td>$\eta = 48.0\text{ cp}$</td>
</tr>
</tbody>
</table>
of vortexes with and without mold powder trapping against the nozzle port angle, $\theta_\alpha$. The occurrence frequencies were determined by eye inspection. Both the occurrence frequencies decreased with an increase in $\theta_\alpha$.

**Figure 6** shows the occurrence frequencies of vortex against the immersion depth, $d$, for the liquid paraffin layer. The two frequencies decreased with an increase in $d$.

These results collectively suggest that the occurrence frequency of vortex is strongly affected by the water flow just beneath the meniscus and the flow approaching the immersion nozzle.

### 3.3. Effect of Water Flow Approaching Immersion Nozzle on Occurrence Frequency of Vortex

The results shown in Figs. 5 and 6 revealed that the vortex formation near the immersion nozzle is closely associated with the port angle, $\theta_\alpha$, and the immersion depth, $d$. The occurrence frequency of vortex was correlated by focusing on the water flow in the mold.

Measurements of water flow velocities, $v_{\text{mL}}$ and $v_{\text{mR}}$, just beneath the meniscus at two positions of 1/4 width and 3/4 width of the wide face as well as observation of the behavior of vortexes near the immersion nozzle were carried out to understand the effect of water flow velocity on the occurrence of vortexes. The subscripts, L and R, denote the left and right hand sides of the mold with respect to the immersion nozzle, respectively. It should be noted that $v_{\text{mL}}$ and $v_{\text{mR}}$ were measured simultaneously.

**Figure 7** shows the relationship between $v_{\text{mL}}$ and $v_{\text{mR}}$. For example, the symbols denoted by open and solid circles denote the appearance of vortexes on the left and right hand sides of the mold, respectively. It is evident that the vortex appears in the lower velocity side, i.e., in the wake of the immersion nozzle. Kubota *et al.* reported that the molten flow velocity beneath the meniscus almost periodically changes its magnitude.

The water flow velocity on the left hand side of the mold changed almost out of phase with that on the right hand side of the mold. Such a nearly periodic flow velocity is considered to be caused by the periodicity of water jets issuing out of the ports of the immersion nozzle.

---

**Fig. 3.** Mold powder trapping by vortex.

**Fig. 4.** Relationships between water flow rate and vortex appearance index.

**Fig. 5.** Relationships between nozzle port angle and vortex appearance index.

**Fig. 6.** Relationships between $d$ and vortex appearance index.
Accordingly, the water flow approaching the immersion nozzle changes its direction alternatively and the Karman’s vortex streets are generated in the wake of the immersion nozzle. The result shown in Fig. 7 suggests that the mold powder trapping is associated with the Karman’s vortex streets.

Figure 8 shows an example of the history of the water flow velocity, \( v_{mc} \), measured beside the immersion nozzle (see Fig. 2). It is evident that \( v_{mc} \) changes almost periodically.

The relationship between the frequency of water flow fluctuation, \( \lambda_{vmc} \) (1/min) and the water flow rate, \( Q_w \), is shown in Fig. 9. The measured value of \( \lambda_{vmc} \) decreased with an increase in \( Q_w \). This result solely cannot explain the reason why the occurrence frequency of vortex has a peak already shown in Fig. 4. The Karman’s vortexes are considered to play a role of triggering the mold powder trapping.

The tip of the Karman’s vortex may be pulled into the mold by a force directed downward near the immersion nozzle. In order to make clear this presumption, measurement of the water flow velocity in the vertical direction was carried out near the immersion nozzle on the right hand side of the mold (see Fig. 2).

The behavior of Karman’s vortexes was simultaneously observed. An amount of a sudden decrease in the vertical velocity, \( v_h \), in 1 s was denoted by \( \Delta v_h \), as shown in Fig. 10. Such a sudden decrease in \( v_h \) seems to be closely associated with the subsequent downward elongation of the Karman’s vortexes. The occurrence frequency of vortex increased with an increase in \( \Delta v_h \). A critical value of \( \Delta v_h \) was 8.6 cm/s.

Figure 11 shows the occurrence frequency of sudden decrease in \( v_h \) for \( \Delta v_h \) greater than 8.6 cm/s against the water flow rate, \( Q_w \). The occurrence frequency increased as \( Q_w \) increased. Accordingly, the sudden decrease in \( v_h \) seems to be caused by the fluctuation of water flow rate at the port of the immersion nozzle.

The above results are schematically shown in Fig. 12. This Figure can qualitatively explain the appearance of a peak in Fig. 4. The mechanism of mold powder trapping near the immersion nozzle in the continuous casting mold can be explained as follows. The Karman’s vortexes are periodically shed in the downstream region of the immersion nozzle. Some of the Karman’s vortexes are pulled deep into the mold due to the downward flow induced by the nearly
periodical fluctuation of water flow at the nozzle port. As a result, mold powder was trapped in the mold. The Karman's vortexes play a role of triggering the mold powder trapping. Although \( \nu_{mc} \) increases with an increase in \( Q_w \), \( \nu_{mc} \) decreases with \( Q_w \) and the occurrence frequency of Karman's vortexes relevant to the mold powder trapping decreases with \( Q_w \) even if the occurrence frequency of \( \nu_h \) greater than the critical value increases.

In other words, when the instance for the occurrence of a Karman's vortex and that for the occurrence of \( \nu_h \) whose value is greater than the critical value overlap each other, that Karman's vortex is pulled deeply into the mold along the immersion nozzle.

The bottom tip of the vortex thus pulled downward is sometimes trapped in the mold.

The effect of water flow issuing out of the port of the immersion nozzle on the downward elongation of Karman's vortex becomes weak with an increase in the port angle, \( \theta_n \), and strong with a decrease in the immersion depth.

### 3.4. Effect of Water Flow on Penetration Depth of Vortex

The penetration depth of vortex, \( D_v \), can be expressed by

\[
D_v = D_{vk} + D_{v\Delta \nu_h} \quad \text{(2)}
\]

where \( D_{vk} \) and \( D_{v\Delta \nu_h} \) are the penetration depth of Karman's vortex and that induced by a sudden decrease in \( \nu_h \), respectively. According to Tanaka et al., \( D_{vk} \) is given by

\[
D_{vk} = \frac{\rho_w}{(\rho_w - \rho_p)} \frac{\nu_{wk}^2}{g} \quad \text{(3)}
\]

where \( \nu_w \) denotes the circumferential velocity of the vortex. It is assumed here to be equal to the horizontal velocity, \( \nu_{mc} \) in the region between the immersion nozzle and the wide face of the mold, and \( \rho_w \) and \( \rho_p \) are the densities of water and the mold powder, respectively.

**Figure 13** shows the relationship between \( D_v \) and \( \Delta \nu_h \) for three kinds of model mold powder. The following equations can be obtained.

\[
D_{v\text{LP}} = 0.026\Delta \nu_h + 0.171 \quad \text{(4)}
\]
\[
D_{v\text{A}} = 0.041\Delta \nu_h + 0.094 \quad \text{(5)}
\]
\[
D_{v\text{B}} = 0.057\Delta \nu_h + 0.213 \quad \text{(6)}
\]

where the subscripts LP, A, and B denote liquid paraffin, silicone oil A, and silicone oil B, respectively.

By assuming that the second terms on the right hand sides of Eqs. (4) through (6) are equal to \( D_{kh} \), the following equation can be derived.

\[
D_v = \frac{\rho_p}{(\rho_w - \rho_p)} \frac{\nu_{wk}^2}{g} + D_{v\Delta \nu_h} \quad \text{(7)}
\]

On the other hand, the following equation can be obtained by assuming that the kinetic energy of model mold powder at an interface between the water and model mold powder layers is equal to the work done by the buoyancy acting on the model mold powder.

\[
\frac{1}{2} m_v \rho_p \Delta \nu_h^2 = g (\rho_w - \rho_p) m_v D_{v\Delta \nu_h} \quad \text{(8)}
\]

where \( m_v \) is the mass of model mold powder pulled into the mold.

The second term on the right hand side of Eq. (7) is replaced by Eq. (9). **Figure 14** shows the measured values of \( D_{v\Delta \nu_h} \), denoted by \( D_{v\Delta \nu_h,\text{obs.}} \), against \( \rho_p \Delta \nu_h^2 / 2g(\rho_w - \rho_p) \). The following equation can be derived from Fig. 14.

\[
D_{v\Delta \nu_h,\text{obs.}} = 0.654 \left[ \frac{\rho_p \Delta \nu_h^2}{2g(\rho_w - \rho_p)} \right]^{0.55} \quad \text{(10)}
\]
Equation (7) is generally expressed by Eq. (11).

\[ D_v = \frac{\rho_w \Delta v^2}{\rho_w - \rho_p} \left( \frac{u_0}{g} \right)^{\alpha} + \alpha \left( \frac{\rho_p \Delta v_h^2}{2g(\rho_w - \rho_p)} \right)^{\beta} \]  \hspace{1cm} (11)

where \( \alpha \) and \( \beta \) are constants, and \( \alpha = 0.654 \) and \( \beta = 0.55 \) in this experiment.

4. Conclusions

Water model experiments were carried out to understand the mechanism of mold powder trapping associated with Karman’s vortexes generated in the wake of the immersion nozzle. Main findings obtained in this study can be summarized as follows.

1. Melted mold powder trapping by the vortex occurred only in the wake of the immersion nozzle.
2. The occurrence frequency of vortex increased with an increase in the water flow rate, had a peak, and then decreased. This tendency is closely associated with the fluctuation of the water flow at the nozzle ports. The maximum value appeared in the water flow rate regime ranging from 61.4 to 70.2 L/min.
3. The penetration depth of mold powder can be given by

\[ D_v = \frac{\rho_w \Delta v^2}{\rho_w - \rho_p} \left( \frac{u_0}{g} \right)^{\alpha} + \alpha \left( \frac{\rho_p \Delta v_h^2}{2g(\rho_w - \rho_p)} \right)^{\beta} \]

Nomenclature

- \( Q_w \): Water flow rate (L/min)
- \( Fr \): Froude number (–)
- \( u_0 \): Average velocity of water flow at one of the two nozzle ports (cm/s)
- \( g \): Acceleration due gravity (cm/s²)
- \( D_{mv} \): Cross-sectional area equivalent diameter of the port (cm)
- \( v_m \): Velocity of water flow below water surface measured at 1/4 width and 3/4 width positions
- \( v_{mc} \): Velocity of water flow below water surface measured at 1/2 width position
- \( v_h \): Vertical velocity of water flow near the immersion nozzle
- \( \theta_n \): Immersion nozzle port angle (°)
- \( d \): Immersion depth (cm)
- \( \lambda_{v_{mc}} \): Occurrence frequency of velocity fluctuation at a position between immersion nozzle and wide face
- \( \Delta v_h \): Occurrence frequency of sudden decrease in \( v_h \)
- \( D_v \): Penetration depth of vortex
- \( D_{vk} \): Penetration depth of Karman’s vortex
- \( v_h \): Circumferential velocity of vortex (=\( v_{mc} \)) (cm/s)
- \( \rho_w, \rho_p \): Densities of water and the model mold powder (g/cm³)
- \( m_v \): Mass of model mold powder pulled into the mold (g)
- \( \alpha, \beta \): Constants (–)

Subscripts

- L, R: Left and right hand sides of mold bath
- w, t: Width and thickness of mold bath
- cal., obs.: Computation value and the measurement value
- LP, A, B: Liquid paraffin, silicone oil A, and silicone oil B

REFERENCES

3) A. Mutou and N. Kasai: CAMP-ISIJ, 10 (1997), 900.