1. Introduction

With increasing casting speed in the conventional CC caster, critical problems such as meniscus-turbulence, generation of longitudinal-vortex at the meniscus and generation of self-excitation-vibration in the bulk mold flow and biased flow from the outlets of the immersion nozzle have become remarkable.1–5) Mold flux entrapment due to vortexing and shearing action from oscillating surface waves have become of particular concern. That is, many quality and productivity limitations of a CC caster are therefore fundamentally linked to metal delivery into the mold.

Recently, effects of swirling flow in the immersion nozzle have been considerably acknowledged: a quite uniform velocity distribution at the outlet of the divergent-immersion nozzle can be easily accomplished, the penetration depth of nozzle outlet flow is remarkably decreased and a uniform velocity distribution can be obtained within a very short distance from the outlet of the nozzle in the billet mold, separation of the flow along the wall of the immersion nozzle can be prevented, the divergent immersion nozzle with swirl is able to turn the flow radially outward without an opposite face on the end of the nozzle,6–8) stable flow-pattern in the slab mold can be obtained9) and so forth.

However, the mechanism of the bulk flow in the slab mold is not fully cleared. Accordingly, the purpose of this study is to understand the mechanism of the bulk flow in the slab mold while swirling motion is imparted to the flow in the immersion nozzle.

2. Experimental Apparatus

Figures 1 and 2 show the schematic illustrations of the experimental apparatus used in the water model. A scale-factor of water model mold 1/2 was used considering a Froude-number of similarity which corresponds to a throughput of 2.2 m/min in a real mold. A constant fluid velocity was obtained through the immersion nozzle using an over-flow tank. The desired swirl flow was established using a fixed twist-tape-swirl-blade (swirl blade) placed at the upstream end of the nozzle tube.10) In order to eliminate swirl from the system the swirl blade could be removed, without changing the system.

Figure 3 shows a schematic of the used immersion nozzle with the circular arc of radius 30 mm at the tip of the outlet which promotes a divergent effect of the flow from the outlet of the immersion nozzle.

KEY WORDS: swirl; immersion nozzle; flow pattern in the mold; S-shaped circulation; swirl flow; continuous casting; meniscus flow; uniform; stable outlet flow.
The inner diameter of the immersion nozzle was 40 mm.

The X, Y and Z direction velocities were measured every 3 mm in each direction using a laser Doppler velocimeter (LDV) mounted on a traversing device. The history of the velocity was measured every 2 sec. A velocity under steady conditions was measured between 20 and 30 sec. The LDV used a 2-dimentional 4 W Ar laser made by Dantec Inc. The working water was seeded with 1 micron alumina powder to facilitate the measurements. The mean velocity through the tube was measured by an electro-magnetic velocimeter and was found to be 1.5 m/s. The resulting Reynolds number was 60 000 for a water temperature of 20°C.

3. Results and Consideration

A radial profile of the tangential velocity at 20 mm downwards from the nozzle entrance is shown in Fig. 4. The calculated solid line was obtained through numerical calculation using a turbulent \( k-e \) model under an axial velocity of 1.5 m/s; a twist ratio of 3/4 and a twisted-tape-swirl-blade thickness of 7 mm. The measured and calculated results fairly coincide with each other.

Figure 5 shows the nozzle configuration used, various
positions to be measured, and flow pattern at the nozzle outlets in the plane through the nozzle axis. Here the magnitude of vector 1 m/s is shown for reference. The greater part of velocity forming the angles from 30 to 45 degree with the horizontal plane come from the upper part of the outlet because the flow through the centrifugal force acting on it streams out along the curved wall of the nozzle. While a slightly upstream stream can be seen on the lowest part of the outlet due to the reverse-flow-effect of the well.

Figures 6 and 7 show the axial profiles of the velocities $V_y$ parallel to the wide face taken at the outlets of the nozzle. The mean velocity appeared to always change randomly at a high magnitude in the absence of swirling flow. It can be considered that the flow makes a separation periodically on the curved wall of the nozzle. When the flow undergoes a separation on the curved wall of the nozzle, it streams straight downward, impinges on the bottom of the nozzle. When the flow sometimes streams out along the nozzle-curve through a kind of Coanda effect, it makes a peak velocity near the upper tip of the outlet of the nozzle. These phenomena occur periodically between 10 and 15 sec later, as shown in Fig. 9. On the other hand, the variations of the velocity in the presence of the swirl motion are very little compared with the mean velocity. The flow always follows along the nozzle-curve through an effect of centrifugal force with imparting a swirling flow in the nozzle and a weak peak appears in a mean velocity near the upper part of the outlet, as shown in Fig. 7.

Figure 8 shows the axial profile of the tangential component of the mean velocity at the outlet. Its largest velocity is
observed near the upper part of the outlet and its variation is very small. It is found that the swirling strength is almost zero near the upper tip and bottom of the outlet of the nozzle and increases linearly with increasing the distance from the both ones.

Figures 9–11 show the quasi-unsteady velocities \( V_y \) measured every 2 sec at the positions shown in Fig. 5. The period of velocity variations without swirl was between 10 and 20 sec and the magnitude of variations was about 4 to 5 times as large as that with swirl. It is considered that the separation of the flow from the curved wall of the nozzle occurs with a period of 10 to 20 sec for the case without swirl, which leads to a considerably large variation as shown in the above-mentioned magnitude. Namely, for the case without swirl, the outlet flow pattern is remarkably fragile because that may be easily affected by a kind of Coanda effect and outer disturbance such as downward flow passing near the upper part of the outlet. On the contrary, it is observed that the variation of the velocity, i.e. uneven flow at the outlet of the immersion nozzle is remarkably suppressed by imparting a swirling flow in the immersion nozzle, because the flow surely follows along the curved wall of the nozzle, namely the flow always attaches to the curved wall through the centrifugal force acting on the flow. It is found that a stable and even outlet flow can be obtained for the case without separation of the boundary layer at the outlet of the nozzle.

Figure 12 shows the velocity distributions on five planes beneath the meniscus, where 1 to 5 indicate the locations measured. The outlet of the immersion nozzle is located between 3 and 4. The outlet flow softly impinges on the side wide face (see the distributions at 3, 4 and 5), and then turns around as a reverse flow along the other wide face describing a S-shaped curve. Figure 13 shows that the outlet flow softly impinges on the side wide face (see the distribution at \( x = +40 \) mm), then turns around through the narrow face, and rises as a reverse flow along the other wide face. The upward velocities at the narrow face and velocities on the meniscus are remarkably decreased compared with the case without swirl later shown in Figs. 15 and 16, respectively because a considerable energy of the outlet flow may be consumed due to the viscous friction loss with the wide mold wall area during impinging at the wide face and turning around as a reverse flow along the other wide face describing a S-shaped curve. As a result, a flow rotating clockwise can be also seen in the vertical sections, as shown in Fig. 14. The time-averaged velocities along the narrow face are shown in Fig. 15, where the upward velocity is much less than that without swirl.

A time-averaged surface flow which is directed towards the immersion nozzle from the narrow face on the meniscus can be observed in Fig. 16, where the magnitude of the velocity in the \( Y \) direction, \( V_y \), with swirl is considerably less than that without swirl and its variations are much less than those without swirl.

A quasi-unsteady behavior can be seen on the history of the velocity in the \( Y \) direction, \( V_y \), measured every 2 sec at a fixed point on the meniscus of the mold, as shown in Fig. 17.
This quasi-unsteady behavior of the surface velocities reveals a high amplitude of oscillation with a period of 10 to 15 sec for the case without swirl. An uprush near the narrow face, depression caused by shearing action due to the high amplitude of waving and a vortex shown in Fig. 18 near the nozzle are observed. The vortex seems to be originated from the separation of the boundary layer when a biased flow on the meniscus shifts from one side of the nozzle to the other side. On the other hand, the magnitude of variation with swirl is less than one fifth of that without swirl. The vortexing, depression and uprush near the narrow face do not exist for the case with swirl as shown in Fig. 18. Namely, considerably stable and calm surface flow is observed with imparting a swirling motion on the flow in the immersion nozzle.

It seems that the stable and even outlet-flow of the immersion nozzle and the above-mentioned complicated flow-path in the mold after flowing out from the immersion nozzle for the case with imparting the swirling motion to the flow in the immersion nozzle prevent the self-excitation flow in the mold. In other words, the steady outlet flow softly impinges on the side wide face, and then turns around as a reverse flow along the other wide face describing a S-shaped curve in the cross section and clock-wise rotational flow in the vertical section, which exerts a shearing-effect on the inner wall of the mold, leads to the considerable energy consumption and exerts a braking effect in the flow which results in suppression of self-excitation-vibration in the bulk mold flow and biased flow on the meniscus. In

Fig. 14. Flow patterns with swirl, at the various vertical sections across mold model. $V_z$ in nozzle, 1.5 m/s.

Fig. 15. Velocity of the narrow face flow with and without swirl.

Fig. 16. Velocity of the surface flow with and without swirl positioned at 11 mm below the meniscus. $V_z$ in nozzle, 1.5 m/s.
other words, imparting a swirling motion to the flow in the immersion nozzle, remarkably reasonable bulk mold flow can be obtained.

4. Conclusions

A swirl motion was imparted to the flow in a reversed Y-shaped immersion nozzle using a twist-tape-swirl-blade inserted into the immersion nozzle, and obtained effects on controlling the flow pattern in the slab mold are as follows:

1) High amplitude of oscillation with a period of 10 to 15 sec was observed in the outlet flow without swirl. On the other hand, the amplitude was remarkably decreased, and hence, even and stable outlet flow could be obtained for the case with swirl.

2) On the meniscus flow, high amplitude of oscillation with a period of 10 to 15 sec and disturbance such as an up-rush, depression and vortex could be observed for the case without swirl. On the other hand, imparting a swirling motion in the immersion nozzle, a decrease in the meniscus flow velocity, remarkable decrease in the amplitude of oscillation, disappearance of vortex and suppression of disturbance, i.e., considerably stable meniscus flow could be observed.

3) The steady outlet flow softly impinges on the side wide face, and then turns around as a reverse flow along the other wide face describing a S-shaped curve in the cross section and clock-wise rotational flow in the vertical section. This outlet flow exerts a shearing-effect on the inner wall of the mold, leads to the considerable energy consumption and exerts a braking effect in the flow which results in suppression of self-excitation-vibration in the bulk mold flow and biased flow on the meniscus. In other words, imparting a swirling motion to the flow in the immersion nozzle, remarkably reasonable bulk mold flow can be obtained.

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