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SWIRLING FLOW EFFECT IN IMMERSION NOZZLE ON BULK MOLD FLOW IN CONTINUOUS CASTING

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ABSTRACT

Swirling flow effectiveness on controlling the bulk mold flow has recently been acknowledged, concerning the productivity and quality of the continuous casting process. In this study, a simple bottomless immersion nozzle equipped with a fixed swirl blade is proposed. From a practical point of view, the relationship between the throughput and the bulk mold flow is investigated. The following results are obtained:

1. Numerical analysis fairly coincides with the experimental results of the velocity distributions at the nozzle outlet, near the meniscus, and near the narrow face.
2. The surface quality of slabs and product coils is obviously improved with the swirling flow immersion nozzle.
3. Even in the high throughput range, stable bulk mold flow can be obtained.

Key Words

swirl; immersion nozzle; high throughput; continuous casting; slab mold; flow pattern in mold; bottomless immersion nozzle.

NOMENCLATURE

L:	Outlet length shown in Fig. 2
d:	Inner diameter of immersion nozzle in Fig. 2
Vz:	Mean axial velocity in Z direction at the nozzle inlet
Vym:	Meniscus flow velocity in Y direction
W:	Mean tangential velocity across the nozzle at the nozzle inlet

INTRODUCTION

With increasing casting speed in the conventional CC caster, critical problems such as unstable bulk mold flow have become remarkable. Mold flux entrapment due to vortexing and shearing action from the oscillating surface waves have become of particular concern (Teshima et al., 1993; Wang, 1990; Tanaka et al., 1992; Gebhard et al., 1993; Tozawa et al., 1993). Therefore, many quality and productivity limitations of a CC caster are fundamentally linked to metal delivery into the mold.

Recently, effects of swirling flow imparted in the immersion nozzle on the quality and productivity of steel have been acknowledged (Yokoya et al., 1994; Yokoya et al., 1994; Yokoya et al., 1998; Mori et al., 1993). The flow pattern in the slab-mold has been investigated within the conventional throughput range and the following results are obtained; Velocity oscillations of high amplitude with a period of 10 to 15 sec were observed both at the nozzle-outlet and in the mold. These oscillations were remarkably suppressed by imparting a swirling flow in the immersion nozzle, which leads to very calm and stable flow patterns at the outlet of the immersion nozzle, in the mold and on the meniscus (Yokoya et al., 2000; Yokoya et al., 2000).

Such effectiveness of swirling flow imparted in the immersion nozzle on the mold flow is also in a trial stage for its practical application. Accordingly, it is urgently needed to investigate the mold flow pattern in the range of high throughput. Therefore, relationship between the configuration of the nozzle-outlet and the molten steel flow pattern was investigated, increasing the throughput from 2.2 m/min the real mold (the conventional throughput presented in preceding paper) to that of two times.

EXPERIMENTAL APPARATUS AND NUMERICAL SIMULATION CONDITION

Figure 1 shows a schematic of the experimental apparatus. The scale factor of a water model was 1/2. The Froude-number similitude was chosen to determine the fluid velocity corresponding to the throughputs of 2.2 to 4.4 m/min in the real mold. A constant fluid velocity was obtained through the nozzle using an over flow tank. The desired swirling flow was established using a fixed swirl blade placed at the upstream end of the nozzle tube. Figure 2 shows a schematic diagram of the bottomless immersion nozzle thus used. The circular arc of a radius of 30 mm at the tip of the outlet promotes a divergent effect of the flow issuing from the outlet of the immersion nozzle with the swirl. 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 LDV used a 2 dimensional 4 W Ar laser made by Dantec Inc. The working water was seeded with 3 micron alumina powder to facilitate the measurements. The history of the velocity was measured every 2 sec. Under steady conditions the velocity was measured every 20 or 30 sec.

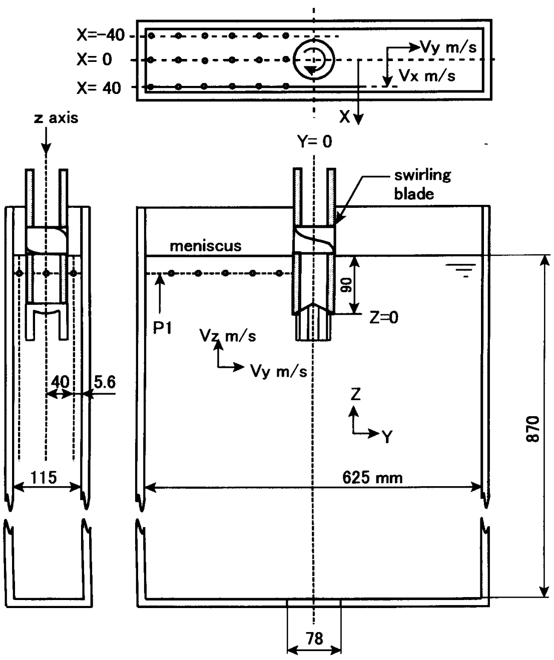


Figure 1: Schematic diagram of model mold, showing swirl blade and positions for measuring velocity.

The cross-sectional mean velocity through the tube was measured by an electro–magnetic velocimeter and was set to be 1.5 m/s (= throughput of 2.2 m/min of the real mold) and 3 m/s (= throughput of 4.4 m/min of the real mold), respectively. The resulting Reynolds number was 60,000 and 120,000 for a water temperature of 20 °C.

The continuity and momentum equations and the k-ε model are adopted for the following calculations using the FLUENT-code (Fluent Inc., 1998). Boundary conditions: the wall function is used at a solid wall; k and ε are those derived from the assumption of an equilibrium boundary layer; uniform axial component velocity and radial profiles of tangential velocity described later are assumed at the nozzle entrance; a constant pressure is assumed at the exit boundary; no shear stress is assumed at the free surface; small grid spacing is employed near the domain. In order to ensure the numerical accuracy of the results, the mass and momentum equations are required to be satisfied within 0.1 % of the integrated flow of the quantity through the domain. At the same time, the grid independence of the numerical results is required.

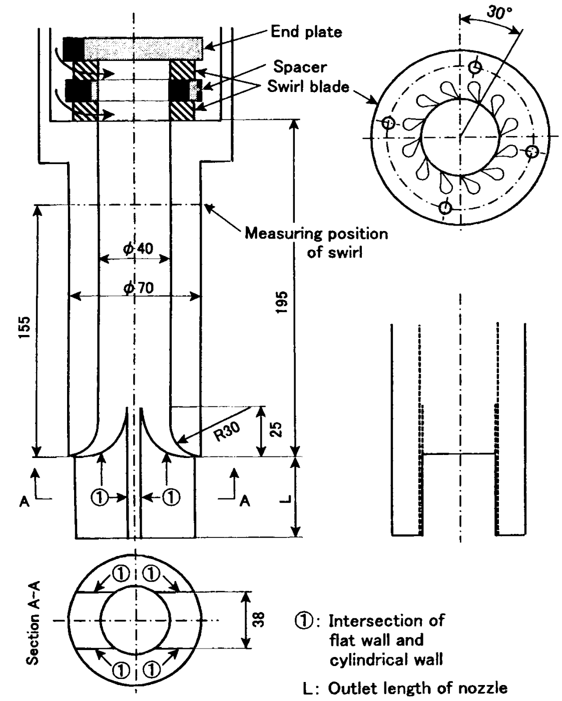


Figure 2: Schematic diagram of bottomless nozzle with swirl blade.

RESULTS AND DISCUSSION

The radial profiles of the tangential velocity at the nozzle entrance are shown in Fig. 3. Figure 4 shows the velocity distributions around the outlet of the nozzle on the symmetric plane of the center section in Fig. 2 in the cases without and with swirl. In the case without swirl, the flow goes straight down and boundary layer separation is observed on the curved wall of the nozzle outlet. On the other hand, in the case with swirl the flow follows along the curved wall of the nozzle through the effect of centrifugal force.

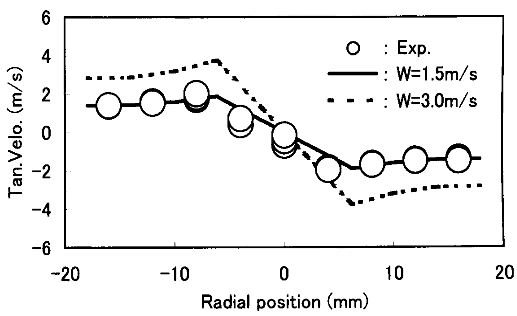


Figure 3: Radial profile of the tangential velocity, W, at the entrance of the nozzle.

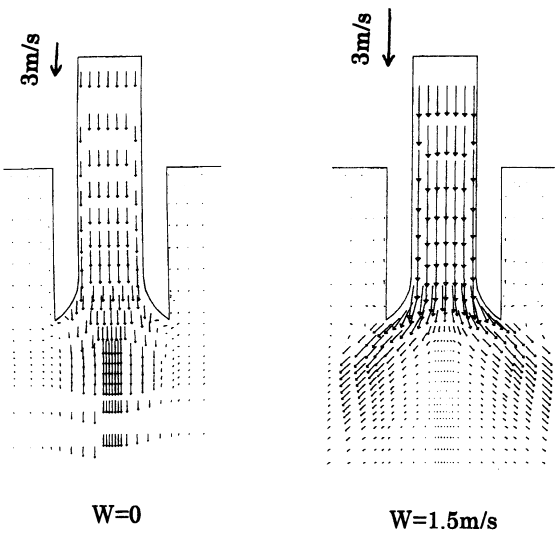


Figure 4: Velocity distributions at the nozzle-outlet in the cases with and without swirl. Vz is 1.5 m/s in the immersion nozzle.

Figure 5 shows the velocity distributions on five horizontal planes beneath the meniscus, where ① to ⑤ indicate the measurement locations. The outlet of the immersion nozzle is located between ③ and ④. The outlet flow impinges on one of the wide faces (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.

The contour maps of the turbulence kinetic energy are shown in Figs. 6. The turbulence energy level is stronger near the narrow and wide faces (X=+40mm) because of the S-shaped curve-effect mentioned above. Accordingly, the turbulence level near the meniscus in the case with swirl is considerably weak compared with that without swirl. Such tendency can also be found in the case of Vz=W=1.5 m/s.

The time averaged surface flows, which are directed from the narrow face towards the immersion nozzle, are found in the cases of axial inlet velocities of 1.5m/s and 3 m/s, as can be seen in Fig. 7. The magnitudes and variations of the velocities in the Y direction, Vym, with swirl are considerably lower than those without swirl. The calculated results coincide well with the experimental

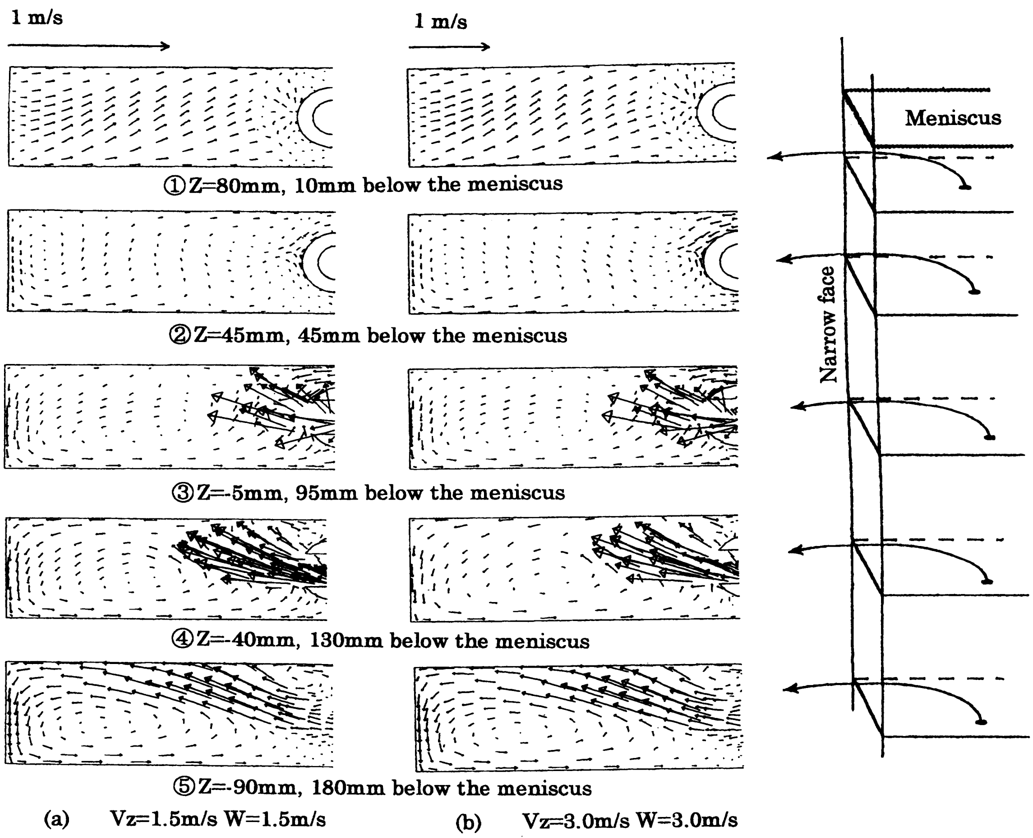
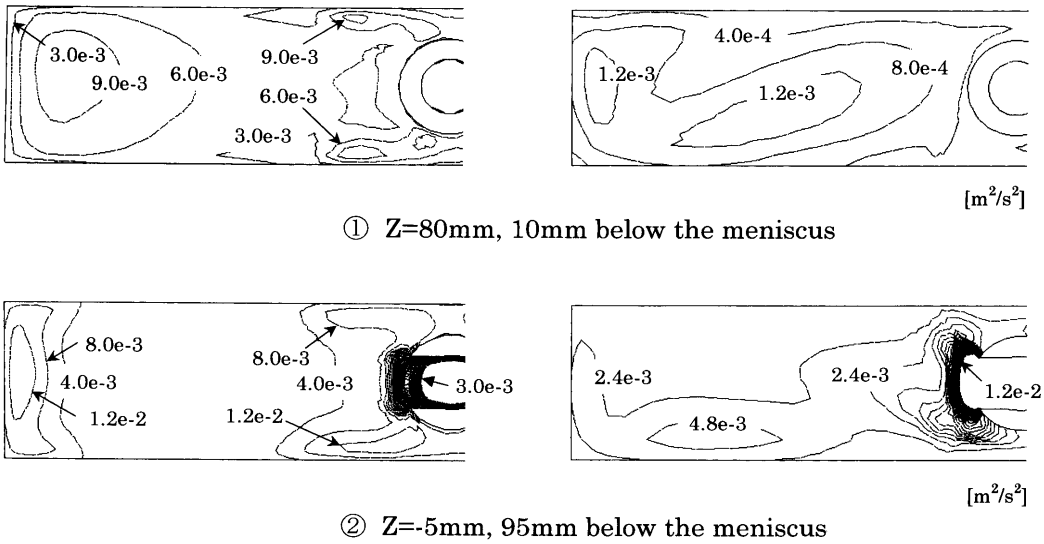


Figure 5: Flow patterns with swirl at various depths below the meniscus, 12, 48, 148 and 198 mm for the water model in the cases; Vz in nozzle, 1.5 m/s and 3 m/s; entrance tangential velocity W, 1.5m/s and 3 m/s



(a) Con. Noz. (Vz=3 m/s, W=0 m/s) (b) Without bot., (Vz=3 m/s, W=3m/s)

Figure 6: Contours of the turbulent kinetic energy, k(m^2/s^2)

results. A quasi-unsteady behavior can be seen on the history of the velocity in the Y direction, Vym, measured every 2 sec at a fixed point on the meniscus of the mold, as shown in Fig. 8. The calculated results are also shown in Fig. 8. This quasi-unsteady behavior of the surface velocities reveals a high amplitude of oscillation with a period of 10 to 15 sec in the case without swirl. Even with twice the conventional throughput, (namely, Vz of 3 m/s in the nozzle), the variation in the case with swirl is within one tenth of fluctuation for the conventional throughput (Vz of 1.5 m in the nozzle) without swirl. The meniscus fluctuation is within 0.04 to 0.06 m/s in the real mold, which is much lower than the critical velocity difference of 0.6 m/s deduced by Iguchi et al. (Iguchi et al., 2000).

The swirling flow immersion nozzle was applied to the wide slab casting, as shown in Table 1 (Tsukaguchi et al., 2002). As a result of the stable flow in the mold, the surface quality of the slabs and product coils is obviously improved with the swirling flow immersion nozzle, as shown in Fig. 9.

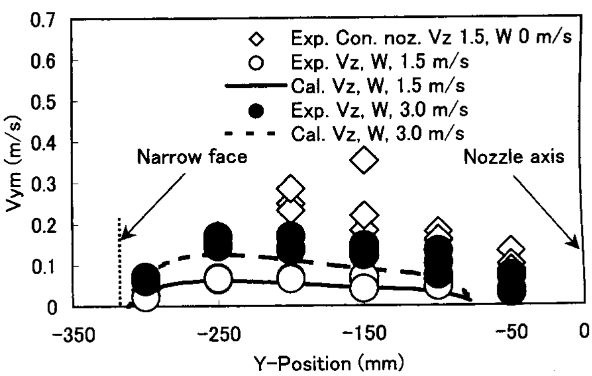


Figure 7: Velocity of the surface flow at 11 mm below the meniscus.

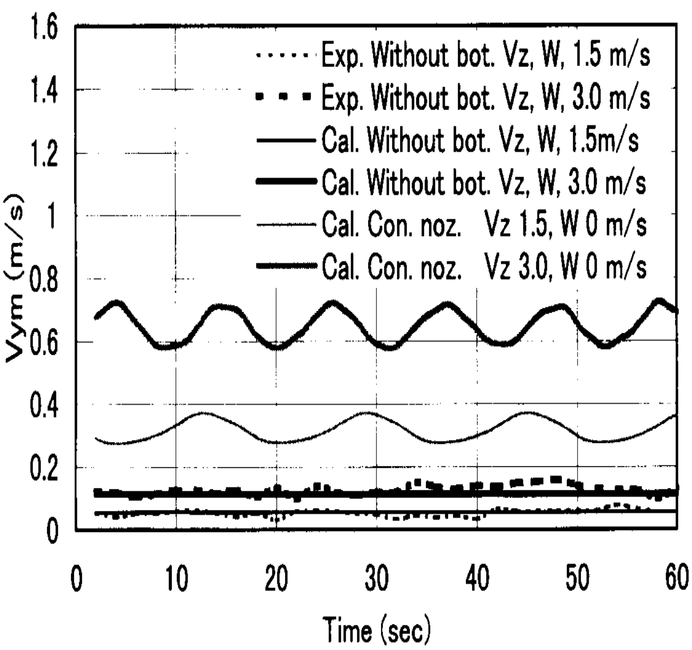


Figure 8: Calculated velocity fluctuation of the surface flow at 11 mm below the surface (Y= - 150 mm at the center line section).

Table 1 Casting conditions of slabs

Items	Specifications	
Mold Size	210t×1780-1880w	
Steel Grade	Ultra Low Carbon Steel for Automobile Panels	
Casting Speed	Swirling Flow Nozzle	Max. 1.5-1.8 m/min.
	Conventional Nozzle	Max. 1.3 m/min.

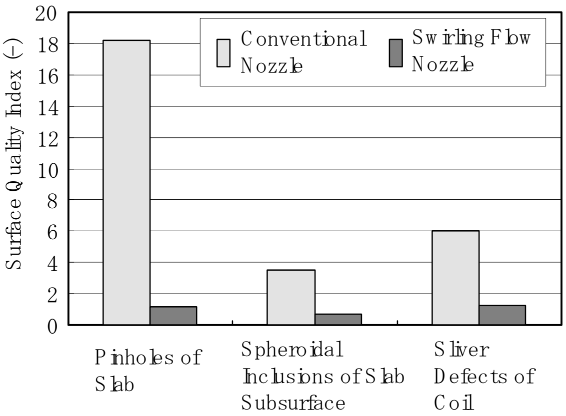


Figure 9: Effect of swirling flow immersion nozzle on surface quality of slabs and coils.

CONCLUSIONS

A swirling motion was imparted to the flow in a reversed Y-shaped immersion nozzle. The obtained effects on controlling the flow pattern in the slab mold are as follows:

Steady outlet flow impinges on the wide face side, and then turns around as a reverse flow along the other wide face describing a S-shaped curve on the horizontal cross section and rotational flow on the vertical cross section. This outlet flow exerts a shearing effect on the inner wall of the mold, leads to a considerable energy consumption and exerts a braking effect on the flow which results in suppression of self-excited-vibration in the bulk steel flow and biased flow on the meniscus. Such an effect can be ascertained because the turbulence level near the meniscus in the case with swirl is considerably weaker than that without swirl. In other words, by imparting a swirling motion to the flow in the immersion nozzle, a remarkably stable bulk steel flow can be obtained. As a result of the stable flow in the mold, the surface quality of the slabs and product coils is obviously improved with the swirling flow immersion nozzle, as shown in Fig. 9.

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