Swirling flow control in immersion nozzle for Continuous Casting process

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It has been acknowledged that swirling motion in the immersion nozzle is very effective to control the bulk mold flow. From the practical viewpoint, it is very reasonable for a swirling strength in the immersion nozzle to be as weak as possible while controlling the bulk mold flow. Here, a gradually diverging immersion nozzle is proposed and its characteristics and its effectiveness on controlling a bulk mold flow are investigated, using a water mold model. Using even considerably weak swirling velocity (0.24 m/s) in a immersion nozzle, maximum velocity at the outlet of the nozzle, surface flow on the meniscus and upward velocity near the narrow face were reduced. However a variation of velocity in those cases was observed.

KEY WORDS: Swirling flow control; diverging immersion nozzle; continuous casting process; bulk mold flow.

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 the oscillating surface waves have become of particular concern. Namely, 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 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, stable flow pattern in the slab mold can be obtained and so forth.¹⁻⁹⁾ The effectiveness of swirling flow in the immersion nozzle is in a trial stage for the practical application.

It is reasonable for a swirling velocity in the immersion nozzle to be as weak as possible, considering economic and simplicity. If a reasonable divergent angle with the diverging immersion nozzle is considered, it seems to be possible that not so large swirl velocity is required to prevent separation from the wall of the immersion nozzle, to control the flow pattern at the outlet of the immersion nozzle and in the bulk mold.

In this study, it is focused on the things that using a diverging immersion nozzle from the inlet to the nozzle-outlet both the mean velocity in the nozzle and the maximum velocity at the outlet are decreased and therefore the flow pattern in the mold is reasonably controlled.

2. Experimental Apparatus

Figures 1 and 2 show a schematic of the experimental apparatus. A scale factor of water model mold 1/2 was used considering a Froude-number of similarity which correspond to a through-put of 2.2 m/min in a real mold. A constant fluid velocity was obtained through the nozzle using an over flow tank. The desired swirl flow was established using a fixed swirl blade placed at the upstream end of the nozzle tube. The cross area of the immersion nozzle used in Fig. 1 is diverging in diameter from the upstream 40 mm to the exit 60 mm in the length, 300 mm.

Fig. 1 Schematic diagram of water model mold.

Fig. 2 Schematic diagram of model mold, showing swirl blade, positions for measuring velocity.

While the straight nozzle with the curved tip of radius of 30 mm of outlet was used in Fig. 2. An immersion depth was set to be 90 mm for the both case. The measuring points in Fig. 1 were same as those in Fig. 2. The axial, radial and tangential velocity profiles were measured every 3 mm in the axial 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.

3. Results and considerations

3.1 Gradually diverging nozzle

Figure 3 shows a change of the calculated radial component of velocity at the nozzle outlet ($A-B=44$ mm) when the swirl strength is gradually increased, using turbulent $k-\epsilon$ model¹⁰.

The velocity distribution changes significantly with an increase of swirl velocity from 0.6 to 0.7 m/s. Below swirl velocity of 0.6 m/s a reverse radial component velocity at the upper part of the nozzle outlet can be seen because of the separation from the wall of the nozzle and a maximum velocity due to the impinging flow near the outlet B can be observed, while over swirl velocity of 0.7 m/s the velocity distribution becomes remarkably uniform and the reverse flow disappears at the upper part of the nozzle outlet.

Fig. 3 Calculated radial component of velocity at the nozzle outlet with a inlet mean axial velocity 1 m/s.

Figure 4 shows a relationship between the critical inlet tangential velocity and divergent angle of the nozzle for the flow not to separate from the wall of the nozzle. Over the divergent angle of 30° the slope becomes considerably gentle. However, the swirling velocity larger than that of 0.7 m/s is required so that the uniform velocity distribution can be obtained, considering the velocity distributions at the nozzle outlet shown in Fig. 3.

Figure 5 shows a comparison of the conventional straight nozzle without swirl with the divergent nozzle with swirl for the axial profiles of the velocity V_y parallel to the wide face taken at the nozzle outlet. In spite of considerably weak swirling velocity of 0.24 m/s, a maximum velocity at the nozzle outlet with swirl was reduced to half that without swirl. Figure 6 shows the V_z -velocity distributions along the narrow face. The maximum "upward velocity" for the case with swirl is decreased to 70% of that without swirl.

Fig. 4 Relationship between critical inlet tangential velocity and divergent angle.

Fig. 5 Profile of horizontal velocity at the nozzle outlet for the case: straight nozzle of inner diameter 40 mm and gradual divergent nozzle shown in Fig. 1.

A time averaged surface flow which is directed towards the immersion nozzle from the narrow face on the meniscus can be observed in Fig. 7, where the magnitude of the velocity in the Y direction, V_y with swirl is considerably less than that without swirl.

Figure 8 shows a bulk mold flow in the water model. The outlet flow impinges on the narrow face, then splits vertically to create the upper and lower recirculation region. The flow pattern is similar to the conventional that observed in the bifurcated nozzle without swirl.

Fig. 6 Velocity of the narrow face flow with and without Swirl.

Fig. 7 Velocity of the surface flow with and without Swirl Positioned at 11 mm below the meniscus. V_z in nozzle, 1.5 m/s.

Fig. 8 Flow pattern with swirl, at the various thickness for the water model. V_z in nozzle entrance, 1.5 m/s.

3.2 Straight nozzle with swirl

Figure 9 shows a flow field in the mold for the case having a axial component velocity 1.5 m/s and swirl velocity 1.5 m/s at the nozzle entrance. The outlet flow softly impinges on the side wide face, then turn around through the narrow face as a reverse flow along the other wide face.

Velocity vectors in the five transverse sections below the meniscus are shown in Fig. 10, where ① to ⑤ indicate the locations measured. The outlet flow softly impinge on the side wide face (see ③, ④, ⑤), and then turns around as a reverse flow along the other wide face describing a S-shaped curve.

Fig. 9 Flow pattern with swirl, at the various thickness for the water model. V_z in nozzle, 1.5 m/s. P, Nozzle outlet.

The variation of velocity in the surface flow which is directed towards the immersion nozzle does not be almost observed as shown in Fig. 11. It seems that the stable surface flow seems to be induced as follows: 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 clockwise 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 a braking effect in the flow which results in suppression of self-excitation in the bulk mold flow and biased flow on the meniscus.

4. Discussion

Considerable variation of velocity shown in Fig. 7 are observed compared with that in Fig. 11. Such a tendency occurs because for the case of gradually diverging nozzle with an weak swirl velocity of 0.24 m/s, S-shaped curve which contribute to both the energy dissipation and braking effects in the bulk mold flow, don't appear in the bulk mold flow.

5. Conclusions

Using considerably weak swirling velocity in the gradually diverging immersion nozzle, following results were obtained;

- 1) Maximum velocity at the outlet of the nozzle can be reduced to half that without swirl compared with a straight nozzle.
- 2) Boundary between the divergent angle of the nozzle vs. swirl strength for the separation from the wall of the gradually diverging nozzle was cleared.
- 3) Surface flow on the meniscus and upward velocity near the narrow face were reduced, however variations in those area were observed because such a weak swirling velocity at the nozzle inlet can not produce a S-shaped curve in the transverse section of the bulk mold flow field.

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Fig. 10 Flow pattern with swirl at the various depths below the Meniscus, 12, 48, 148 and 198 mm for the water model. V_z in nozzle, 1.5 m/s.

Fig. 11 Velocity of the surface flow with and without swirl positioned at 11 mm below the meniscus. V_z in nozzle, 1.5 m/s.

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