Swirling Flow Effect in Off-center Immersion Nozzle on Bulk Flow in Billet Continuous Casting Mold

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(Received on March 7, 2001; accepted in final form on July 25, 2001)

It often occurs that setting up an immersion nozzle on the mold, nozzle axis does not coincide with the mold-axis. In this study, under the off-center nozzle with the mold-axis, bulk mold flow was investigated, and following issues were obtained:

- 1) For the case without swirl, the peak of the flow moves near the mold-wall with flowing down from the outlet of the nozzle due to the Coanda effect (shown in Appendix).¹⁾ On the other hand, peak of the flow moves near the mold-axis with flowing down from the nozzle-outlet within considerable short distance, namely axisymmetric velocity distribution can be obtained within very short distance from the nozzle-outlet.
- 2) The surface flow patterns between coaxial and off-center nozzles are quite different. The flow pattern with coaxial nozzle is axisymmetric and simple, while the flow from one side to other side can be observed, with off-center nozzle.

KEY WORDS: off-center immersion nozzle; swirling flow in immersion nozzle; uniform velocity; billet continuous casting mold.

1. Introduction

Recently, it was acknowledged that imparting a swirl to the flow in the immersion nozzle, improvement of productivity and quality of steel ingot concerning CC process are promoted in a trial stage for the practical application. (1) By changing swirl strength, it is easy to control the flow pattern as well as the direction of the flow, (2) Uniform velocity distribution can be obtained within a short distance from the outlet of the immersion nozzle, (3) Heat and mass transfer near the meniscus can be remarkably activated compared with a conventional straight type immersion nozzle without swirl, (4) Swirl helps the superheat in the melt dissipate, (5) Penetration depth of the nozzle outlet flow is decreased remarkably by the application of swirling. Those findings mentioned above are very useful to control the flow pattern in the billet and bloom continuous casters.²⁻⁴⁾ It is considered that setting an immersion nozzle on the billet mold, it is often occurred for the immersion nozzle-axis to not coincide with the billet-mold. In those cases, it is important to investigate how to have an effect on imparting a swirl to the fluid flow in the immersion nozzle.

2. Experimental Apparatus

Figure 1 shows a schematic of the experimental appara-

tus used in the water model, where the off-center distance of the nozzle axis from the mold axis are 15 mm and 30 mm, respectively. 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. In order to eliminate swirl from the system the swirl blade could be removed, without changing the system.

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 Inc. The water was seeded with 3 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 2 m/s. The resulting Reynolds number was 38 000 (for water temperature of 20°C) giving a moderately turbulent flow.

3. Results

Continuity, momentum equations, RNG k - ϵ model for the case without swirl and RSM model for the case with swirl are adopted at the following calculations using the FLUENT-code.^{5,6)} Boundary conditions: wall function at solid wall; k and ϵ are those derived from the assumption of

Fig. 1. Experimental apparatus with off-center nozzle; V_z , mean axial velocity in nozzle; W , mean inlet tangential velocity in nozzle; δ , off-center distance.

Fig. 2. Radial profile of tangential velocity measured at position of 20 mm downwards from the nozzle entrance.

an equilibrium boundary layer; uniform axial component velocity and radial profiles of tangential velocity described later are assumed, at the nozzle inlet; a constant pressure is assumed at exit boundary; no shear stress is assumed at the free surface; small grid spacing was employed near the domain. In order to ensure the numerical accuracy of the results, the mass and momentum equations are required to be satisfied to within 0.1% of the integrated flow of the quantity through the domain.

A radial profile of the tangential velocity at 20 mm downwards from the nozzle entrance is shown in Fig. 2, which is stirred by the swirling blade installed at the entrance of the nozzle. It is noted that Rankin-vortex having both the forced vortex (namely, tangential velocity $w=r\omega$) in the inner region ($r < 15$ mm) and free vortex (namely, tangential velocity $w=K/r$) in the outer region ($r > 15$ mm) can be seen in Fig. 2, and its mean tangential velocity equals 1.72 m/s. From now on, the tangential mean velocity W is denoted by the mean tangential velocity across the nozzle entrance.

$$\text{Uneven velocity} = \frac{|\Delta u|}{V} \times 100 (\%)$$

$$r^* = \frac{r}{R}$$

Fig. 3. Uneven velocity defined.

Fig. 4. Radial profiles of axial velocity vs. several axial positions from the outlet of the immersion nozzle under the off-center distance of 15 mm; without (a) and with swirl velocity W 1.7 m/s (b), V_z in nozzle 2 m/s.

Fig. 5. Radial profiles of the uneven velocity at various axial positions from the outlet of the immersion nozzle under the off-center of 15 mm; without (a) and with swirl velocity W 1.7 m/s (b), V_z in nozzle 2 m/s.

Fig. 6. Radial profiles of axial velocity vs. several axial positions from the outlet of the immersion nozzle under the off-center distance of 30 mm; without (a) and with swirl velocity W 1.7 m/s (b), V_z in nozzle 2 m/s.

3.1. Uneven Flow

Figure 3 shows an uneven velocity defined in this study. A magnitude of uneven flow is defined as follows:

$$\text{Uneven velocity} = |\Delta u| / V \times 100\%$$

where Δu denotes velocity difference, and V represents the mean velocity across the mold.

The development of axial velocity with flowing down from the nozzle-outlet are shown for the cases with and without swirl under the off-center distance of 15 to 30 mm, in **Figs. 4** and **6**, respectively. It can be seen that, for the case without swirl, the flow has a maximum, which is very high on the nozzle axis and considerable velocity fluctuation because of separation of boundary layer. And hence, the accordance between the calculated and experimental results is not so good as shown in **Fig. 4(a)**, especially for the nozzle-axial region. In contrast, for the case with swirl, a maximum velocity reduces to 25% of that without swirl, and a velocity profile becomes both very uniform and calm within a very short distance downwards from the nozzle outlet. The results of the calculation with swirl in **Fig. 4(b)** show the same tendency as the experimental results.

Developments of the uneven velocity defined in **Fig. 3** corresponding to **Figs. 4** and **6** are shown in **Figs. 5** and **7**,

respectively. Considerable uneven velocity for the case without swirl is observed at 200 mm downwards from the nozzle-outlet. In contrast, uneven velocity is nearly zero at 100 mm downstream of the nozzle-outlet. In other words within 100 mm from the nozzle-outlet an almost calm and axi-symmetric flow can be obtained. Therefore, accordance between the experimental and calculated results with swirl is much better compared with that without swirl. Numerical model does not reproduce the experimental results for the case having the boundary-separation between the flow and curved wall of the nozzle-outlet. **Figure 8** shows the velocity variations near the immersion nozzle outlet for the cases with and without swirl. For the case near the nozzle outlet-wall-curve without swirl, considerable magnitude of variation can be observed, on the other side, at the radial positions of 0 and 60 mm from the mold axis where the outlet flow do not directly operate, those variations are neglected. The outlet flow is considerably fragile because that may be easily affected by a kind of Coanda effect and outer disturbance such as downward flow passing near the outlet of the nozzle. In contrast, the fluctuations are remarkably suppressed for the case with swirl, because the outlet flow always surely follows the curved wall of the nozzle-outlet. **Figure 9** shows the relationship between maximum uneven

Fig. 7. Radial profiles of the uneven velocity at various axial positions from the outlet of the immersion nozzle under the off-center of 30 mm; without (a) and with swirl velocity W 1.7 m/s (b), V_z in nozzle 2 m/s.

Fig. 9. Maximum uneven velocity at various off-center distances; with and without swirl, downstream distances of 5 to 200 mm from the nozzle outlet.

velocity and off-center distance for the cases without and with swirl. **Figure 10** shows the relationships between maximum relative uneven velocities (maximum uneven velocity with swirl/maximum uneven velocity without swirl) and off-center-distances.

At the downstream distance of over 100 mm from the nozzle outlet, the maximum uneven velocity is a tenth less than that without swirl. Imparting a swirl to the flow in the

Fig. 8. Velocity fluctuations near the outlet of the immersion nozzle for the cases with and without swirl, at the various radial positions from the mold axis.

Fig. 10. Relative uneven velocity at various off-center distances for the downstream distances of 5 to 200 mm from the nozzle outlet.

immersion nozzle, calm and axisymmetric bulk mold flow can be obtained within a short distance from the immersion nozzle-outlet. **Figure 11** shows the surface flows for the off-center distances δ of 0 to 30 mm. The surface flow pattern between coaxial and off-center nozzle is quite different. The flow pattern with coaxial nozzle is axisymmetric and simple, while the flow from one side to other side can be observed, with off-center nozzle as shown in **Fig. 12**.

Fig. 11. Surface flow patterns and those oblique views for off-center distances of δ at 5 mm below the meniscus: V_z in nozzle 2 m/s, swirl velocity 1.7 m/s.

4. Conclusion

(1) Axisymmetric flow can be obtained within 100 mm downwards from the outlet of the immersion nozzle, with swirl, even with the off-center distance of 30 mm between the axis of nozzle and mold.

(2) The peak of axial velocity distribution without swirl moves near the mold wall with streaming down from the outlet of the nozzle.

(3) Numerical analysis can reproduce well the experimental results for the case imparting a swirl flow in the immersion nozzle, however, don't well for the case without swirl because of the boundary separation between the curved wall of the nozzle outlet and flow.

(4) The surface flow patterns between coaxial and off-center nozzle are quite different. The flow pattern with coaxial nozzle is axisymmetric and simple, while the flow from one side to other side can be observed, with off-center nozzle.

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Appendix¹⁾

A two-dimensional or three-dimensional single-phase jet moving near a wall is pulled towards the wall, attaches to it and finally moves along it. This phenomenon is caused through the Coanda effect, as explained briefly in the following.

We consider, for example, an axisymmetrical, vortical single phase jet. If there is no wall around the jet, the pres-

Fig. 12. Flow patterns at the sections of AA and BB for the various off-center distances of δ shown in Fig. 11: V_z in nozzle 2 m/s, swirl velocity 1.7 m/s.

sure of fluid surrounding the jet is uniform in any horizontal plane because the fluid is uniformly entrained into the jet from all direction in that plane. As a result, the jet moves straight downward. On the other hand, if a wall exists besides the jet, the pressure of fluid between the jet and the

wall decreases compared with the pressure of fluid located on the opposite side of the wall as the jet develops in the vertical direction. According to this pressure difference, the jet is pulled towards the wall and attaches to it.