1. Introduction

With the growth of continuous casting, both experimental and numerical work has been carried out to study the fluid flow in the mould. During the continuous casting of steel, transient flow is very important to the strand quality, and the level fluctuation is believed to have significant contribution to mould powder entrapment. So, control of fluid flow and level fluctuation plays an important role in attaining a better product quality.

For the study of internal flow instability in the mould, Robertson et al.\(^1\) found that the flow asymmetry in a slab mould was either fluctuating or persistent. Gupta et al.\(^2\)–\(^4\) carried out a water model and found that the flow pattern in the mould was oscillating and asymmetric about the central plane with a random period. Gupta also found the non-uniform flow at the mould exit and pointed out that these non-uniform discharge characteristics were directly related to the asymmetric recirculation pattern. Honeyands et al.\(^5\) constructed a 1:6 scale model of the thin slab caster water model to investigate the time dependent flow phenomena and observed that the fluid condition were neither steady nor symmetrical, and instead oscillated periodically. Honeyands pointed out that the interaction between the confined jets and the recirculating fluid eddies could be a critical factor responsible for the oscillation in the thin slab flow system. Ramos-Banderas et al.\(^6\) studied the fluid flow of water in the slab mould using Digital Particle Image Velocimetry (DPIV) and found that the asymmetry of fluid flows and the flow pattern changed with time as a consequence of the vertical oscillation of the jet core. The jet angle and its impinging position on the mould narrow face varied with time corroborating the oscillatory motion of the entry jet. Vanka and Thomas et al.\(^7\),\(^8\) studied the fluid flow in a 0.4-scale water mould using Particle Image Velocimetry (PIV) and the Large Eddy Simulation (LES) methods and found that the flow in the upper region was oscillating between a large single vortex and multiple vortices of various smaller sizes. Davidson et al.\(^9\)–\(^10\) observed the jet oscillation in thin slab continuous casting using a two-dimensional transient numerical model and found that the oscillation relied on the exchange of fluid between recirculation cells on each side of the jet via a cross-flow through the gap between the nozzle shaft and the broad face of the mould. Davidson et al.\(^11\) also used Laser Doppler Anemometry (LDA) measurements in a 1:3 scale water model of the thin slab casting mould with two lateral jets through a bifurcated nozzle and found that the time averaged flow pattern was almost symmetric across the broad face of the mould.

For the study of level fluctuation in the mould, Matsushita et al.\(^12\) measured the meniscus of the molten steel directly through a quartz glass window mounted on the mould wall and found that the meniscus was not stationary but fluctuated at the same period and phase as those of mould oscillation. Gupta et al.\(^13\) found that the meniscus profile kept on fluctuating and was not always symmetric on either side of the nozzle, but the time-average value showed a symmetric pattern. Miranda et al.\(^14\) studied the free surface fluctuations using a 1:3 scale cold water model and found that the free surface level fluctuation showed an...
erratic behavior. Ramírez-López et al. studied the structure of the turbulent flow in a slab mould using a water model and mathematical simulation and found that the meniscus stability depended on the turbulence structure of the flow in the mould.

It is known that the fluid flow is much turbulent in the continuous thin slab casting and the flow instability may be much complicated in the specified mould. A quantitative description of the instability of the fluid flow and level fluctuation in the mould can be relied on design of the SEN structure and the process parameters. The present work aims to investigate the relationship among the flow instability characters such as circumfluence position, level fluctuation and wave height by using a full scale funnel type continuous thin slab casting mould.

2. Experimental

Direct observation of fluid flow in the real mould during continuous casting is very difficult, or even impossible. For this reason, the present study was performed using a full scale water model with the dimension of a practical mould and a two-port down-through submerged entry nozzle (SEN). The full scale water model satisfies Reynolds–Froude similarity requirements, which means that what is observed in the water model reasonably represents the phenomena occurring in the prototype. Figure 1 shows the water modeling experimental setup of continuous thin slab casting consisting a mould, a tundish and a water reservoir. A stopper with height adjustment was used for flow rate control. The flow circuit of water model led fluid from the reservoir to the tundish, then the fluid was discharged into the mould via the two-port down-through SEN and finally returned back into the reservoir. The flow circuit was maintained by a centrifugal pump. The water level in the tundish was kept stable using two baffles and an overflow pipe. To monitor the flow rate through the water modeling system, an electromagnetic flow meter was installed between the mould and the reservoir. The mould was made in Plexiglas with width of 1600 mm and thickness at the mould outlet of 70 mm. In order to find detail flow information near the mould outlet, the height of experimental mould was extended to 2000 mm. SEN immersion depth i.e., the distance from the meniscus to the SEN bottom was 255 mm. The experiment was carried out with the casting speed of 6.0 m/min. To ensure an even outflow from the bottom of the mould, some holes were spaced uniformly on mould bottom. The SEN was fixed strictly at the mould center and the geometrical construction of the mould was symmetrical.

Figure 2 shows a photo of the fluid flow along the mould broad face using the particle image visualization method. In order to quantitatively analyze the circumfluence region and the circumfluence center position with time, the grids in size of 50 mm×50 mm were marked on the mould broad face along the mould width direction. Figure 2 shows a photo of the fluid flow along the mould broad face using the particle image visualization method. In order to quantitatively analyze the circumfluence region and the circumfluence center position with time, the grids in size of 50 mm×50 mm were marked on the mould broad face along the mould width direction. Figure 2 shows a photo of the fluid flow along the mould broad face using the particle image visualization method. In order to quantitatively analyze the circumfluence region and the circumfluence center position with time, the grids in size of 50 mm×50 mm were marked on the mould broad face along the mould width direction.
Fig. 3. Definition of circumfluence center position ($X, Y$) and wave height ($W$).

Fig. 4. Meniscus profile and probabilities of the fluctuated wave positions along the mould broad face.

Fig. 5. Position and probability of circumfluence center along the mould broad face.

3. Results and Discussion

3.1. Instability of Level Fluctuation

From the experiment, it is found that the meniscus is unstable and the liquid level fluctuates with time in the mould. The average meniscus wave profile during the monitoring time of 512 s is shown with a dense line in Fig. 4. The typical meniscus profile in the mould looks like a saddle with two crests near the mould narrow faces and two valleys near the mould centerline where the SEN locates. In order to describe the instability of meniscus, the highest and the lowest positions of the meniscus are marked around the averaged meniscus profile and the probability of the fluctuated wave position by the highest and the lowest positions of the meniscus are also illustrated in Fig. 4. The dashed line in Fig. 4 indicates the average liquid level along the mould width. The average wave profile, the highest and the lowest positions of the meniscus as well as the probability of the fluctuated wave position in Fig. 4 are generally symmetrical about the mould centerline. The average wave height of the meniscus i.e., the average of the left and the right wave heights is 6.7 mm. The range of the fluctuated meniscus between the highest and lowest positions is about 25.4 mm. The probabilities of the fluctuated wave at 12 wave height sensor positions look like Possion distributions with the maximum frequency near the average wave height and the minimum frequency near the highest and the lowest positions of the meniscus. It is known that the steel slag interfacial disturbances should be kept a minimum to avoid any entrainment of impurities into steel. So, these characteristic values can be recommended as guidance to quantitatively analyze the flow conditions at the meniscus of continuous casting.

3.2. Instability of Fluid Flow in Mould

For the two-port SEN with the outlet angle directly downward, the jets from each port of SEN are discharged to the mould bottom and the part of fluid flows back to the meniscus as shown in Fig. 2. In this case, it is hard to find the impinging area at the mould narrow face, so only two dominant circumfluences occupy in the left and the right sides of mould centerline with rotation directions in clockwise and anticlockwise respectively. According to the movie of particle image visualization, it is found that the circumfluence area and the circumfluence center swings with time. Figure 5 shows the positions of the two circumfluence centers with scattered dot and the probabilities of the circumfluence center position along the mould width and height. The moving range of two circumfluence centers is about 200 mm in mould width and 500 mm in mould height direction. The average position of the left circumfluence center is at ($X_L, Y_L$) and the right one is at ($X_R, Y_R$). The probability of the moving circumfluence center is like a Possion distribution with the maximum value of about 0.2 near the average circumfluence center. Both the occurring position and its probability of circumfluence center are generally symmetrical about mould centerline. Figure 6 shows the trajectories of two swing circumfluence centers. It is found that the left circumfluence center moves in counter-clockwise while the right circumfluence center moves in clockwise, and they all move around their average circumfluence center position with a certain period ($T$) and a similar trace.

3.3. Relation of Level Fluctuation and Fluid Flow

In order to explore the influence of swing circumfluence on the fluctuated meniscus, two characteristic points near
the meniscus valley were selected with the wave sensor marked numbers of L4 and R4 as indicated in Fig. 1. Figure 7 shows the variation of circumfluence center positions ($X_L, Y_L$ and $X_R, Y_R$), level fluctuation at characteristic points ($F_{L4}$, $F_{R4}$) and wave heights ($W_L$, $W_R$) in two sides of mould centerline. It is found that the circumfluence center, level fluctuation and wave height vary with a similar period of about 23.3 s during the monitoring time of 512 s. The wave height ($W_L$, $W_R$) is coherently related to the fluctuation near the meniscus valley ($F_{L4}$, $F_{R4}$) with the opposite variation, i.e., the wave height increases with decreasing fluctuation near the meniscus valley. The wave height variation has a same phase with the circumfluence center position along the mould height ($Y_L$ and $Y_R$), and there is a phase difference about a quarter of period between the circumfluence center position along the mould width ($X_L$ and $X_R$) and that along the mould height ($Y_L$ and $Y_R$). The wave height increases with rising circumfluence while circumfluence center departs from the SEN, and the wave height decreases with descending circumfluence while the circumfluence center approaches to the SEN. Therefore, the movement of meniscus is mainly depends on swing of circumfluence. Comparing Figs. 7(a) and 7(b), it can be found that the phase difference of both the wave height and circumfluence position in the left and the right sides of mould is about half period. According to the parameters variation in Fig. 7, the phase differences of wave height, characteristic level fluctuation and circumfluence position are indicated in Table 1 with the reference phase of wave height in the mould left.

Table 1. Phase differences of wave height, characteristic level fluctuation and circumfluence position.

<table>
<thead>
<tr>
<th></th>
<th>wave height</th>
<th>fluctuation at meniscus valley</th>
<th>circumfluence center position in mould height</th>
<th>circumfluence center position in mould width</th>
</tr>
</thead>
<tbody>
<tr>
<td>In mould left side</td>
<td>0</td>
<td>T/2</td>
<td>T/4</td>
<td>T/2</td>
</tr>
<tr>
<td>In mould right side</td>
<td>T/2</td>
<td>T</td>
<td>3T/4</td>
<td>T</td>
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</tbody>
</table>
The relation of circumfluence center position and level fluctuation can be described more clearly in Fig. 8, which indicates the variation of circumfluence center position and meniscus profile in an arbitrarily period from the monitoring time of 50.75–74.00 s in Fig. 7. In order to investigate the evolution of meniscus profile and circumfluence center position, eight intervals is equally divided in the period. For a moment, the circumfluence center position and wave profile is not symmetrical about the mould centerline. For example, at the 1/8 period the meniscus valley in the mould left side is at the lowest position and the circumfluence center position in the mould left side is at the highest, while the meniscus valley in the mould right side is at the highest position and the circumfluence center position in the mould right side is at the lowest (as indicated with number 1 in Fig. 8). After half period, this asymmetry of both circumfluence and meniscus reverses in mirror about the mould centerline. According to the characteristic of meniscus profiles with the same time interval, it is found that the meniscus fluctuates more quickly when the meniscus valley is near to the lowest position.

Figure 9 shows quantitative relation of the wave height \( W \) with circumfluence position along the mould height \( Y \). It can be seen that they have inverse relation. However, it is sure that there is a relation of the wave height \( W \) with the circumfluence position along the mould width \( X \) because there is a phase difference between the circumfluence center position along the mould width and height.

According to the foregoing results, it can be found that the level fluctuation is decided by the instabilities of fluid flow, which is characterized by the period and the swing aptitude of the circumfluence in the continuous casting mould. It is estimated that these characteristic values would be affected by the SEN structure and the process parameters. Therefore, a further investigation on the optimization of the SEN structure and the process parameters with certain instabilities criteria for the practice will be helpful for the control of level fluctuation and fluid flow in the continuous thin slab casting.

### 4. Conclusions

The instability of level fluctuation and fluid flow in continuous thin slab casting mould with a two-port downthrough submerged entry nozzle has been investigated by wave measurement and particle image visualization in a full scale water modeling system. Conclusions are summarized as following:

1. The circumfluence center swings and the meniscus profile fluctuates with time. The probabilities of fluctuated meniscus and swing circumfluence center position seem Poisson distributions with the highest frequency near the average position.
2. The level fluctuation and circumfluence movement is periodical with a similar period. The circumfluence and meniscus profile may be asymmetrical for a moment, and the phase difference of wave height and circumfluence center in the two sides of mould centerline is half period. However, the average circumfluence center position, the average meniscus wave profile, the highest and lowest meniscus positions are generally symmetry about the mould centerline, and circumfluence center swings with a similar trace.
3. The wave height mainly depends on the circumfluence position with constant process parameters. The wave...
height has an inverse relation with the circumfluence center position in mould height, and the wave height decreases with descending circumfluence.

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REFERENCES