Physical Modeling of Asymmetrical Flow in Slab Continuous Casting Mold due to Submerged Entry Nozzle Clogging with the Effect of Electromagnetic Stirring

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Submerged Entry Nozzle (SEN) clogging is a serious problem for continuous casting process and slab quality. In order to investigate the impact of the SEN clogging rate on the flow field and the optimization effect of electromagnetic stirring (EMS) on the asymmetrical flow due to the SEN clogging, a 1:5 scaled mercury model, with various SEN clogging rates and different electromagnetic stirring currents was established and the flow velocity was measured by means of Ultrasonic Doppler Velocimetry (UDV). S index is introduced to judge quantitatively whether the horizontal flow pattern is symmetrical or not. The results show that the symmetry of the flow pattern in the mold becomes broken with the increase of the SEN clogging rate. In this study, EMS is an effective method to increase S index and active the free surface flow when the SEN clogging rate is under 50%. However, the stirring current of EMS should be controlled to avoid the adverse surface flow which may induce slag entrapment.

KEY WORDS: continuous casting; SEN clogging; physical model; S index; electromagnetic stirring.

1. Introduction

Submerged Entry Nozzle (SEN) clogging has been a long-term issue for steel continuous casting process, which may restrict productivity since interrupting the continuous casting process, restricting the number of charges per tundish, lowering the quality of slab and consequently increasing customer rejections.

Most current researches are mainly focused on the mechanism of the SEN clogging, the prevention method, and the impact on the flow field in the continuous casting mold. Both the flow field and the velocity of the free surface have a significant influence on the slab quality. But, only few are performed to study the influence of the rate of the SEN clogging on the flow field in the mold. Srinivas et al. studied the influence of the clogging degree on the flow field through a water model. As an effective method, electromagnetic stirring (EMS) technology can control the molten steel flow in the mold, and has been widely applied in continuous casting process. However, very little fundamental work regarding the optimization of EMS on the broken flow due to the SEN clogging has been reported. It needs to be further researched.

The purpose of this paper is to provide a new method to improve the disadvantageous flow due to the SEN clogging. The influence of the rate of the SEN clogging rate on the flow field and the surface flow are considered. Furthermore, EMS is introduced to investigate its optimization effect on the unfavorable flow because of the SEN clogging. The measurement of the flow velocity was performed in a 1:5 scaled mercury model with the help of Ultrasonic Doppler Velocimeter (UDV). At last, a reasonable EMS operating current is suggested.

2. Experimental Methodology

A 1:5 scaled mercury model has been established to investigate the behavior of liquid metal in the continuous casting mold. The schematic of the experimental setup, shown in Fig. 1(a), consists of the tundish, the mold, the submerged entry nozzle (SEN), two slots, the electromagnetic pump (EM pump), the Ultrasonic Doppler Velocimetry (UDV) and the electromagnetic stirrer. The mercury is discharged from the tundish through a SEN into the mold. Then, the EM pump circulates the metal from the mold bottom back to the tundish. During this process, the flow of mercury is measured by a flowmeter located in the pipe and controlled by a flow valve located near the flowmeter. To ensure an even uniform outflow from the mold bottom, two slots with several holes are installed above the mold exit. The midpoint of the mercury surface has been chosen as the coordinate origin. The directions of the coordinate axis are shown in Fig. 1(a). Some other parameters of the mercury modeling can be found in Table 1. Some properties of mercury and molten steel are listed in Table 2. Froude number, Magnetic interaction parameter, and Magnetic shielding number are chosen to guarantee the similar-
Table 1. Parameters of actual and experimental model.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Actual model</th>
<th>Physical model</th>
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<tbody>
<tr>
<td>Mold width (mm)</td>
<td>1 500</td>
<td>300</td>
</tr>
<tr>
<td>Mold thickness (mm)</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>Mold height (mm)</td>
<td>800</td>
<td>750</td>
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<tr>
<td>Inner diameter of SEN (mm)</td>
<td>170</td>
<td>34</td>
</tr>
<tr>
<td>External diameter of SEN (mm)</td>
<td>80</td>
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<tr>
<td>Submerged depth of SEN (mm)</td>
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<td>25</td>
</tr>
<tr>
<td>Port height of SEN (mm)</td>
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<td>16</td>
</tr>
<tr>
<td>Port width of SEN (mm)</td>
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<td>12</td>
</tr>
<tr>
<td>Port angle of SEN (°)</td>
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<td>−15</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
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<td>50</td>
</tr>
<tr>
<td>Turn number of coil</td>
<td>24</td>
<td>72</td>
</tr>
</tbody>
</table>

Table 2. Properties of mercury and molten steel.

<table>
<thead>
<tr>
<th></th>
<th>Molten steel</th>
<th>Mercury</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (kg/m³)</td>
<td>7 200</td>
<td>13 600</td>
</tr>
<tr>
<td>Conductivity (S/m)</td>
<td>7.14e5</td>
<td>1.01e6</td>
</tr>
<tr>
<td>Viscosity (Pa·s)</td>
<td>0.0055</td>
<td>0.00155</td>
</tr>
</tbody>
</table>

where \( u \) is flow velocity of liquid metal; \( g \) is acceleration of gravity; \( L \) is characteristic length of model; \( \sigma \) is conductivity of liquid metal; \( B \) is magnetic flux density; \( \rho \) is density of liquid metal; \( \mu \) is permeability of liquid metal; \( f \) is frequency of the power.

According to the same Froude number, the ratio of the actual casting speed and the physical casting speed should be \( \sqrt{5} \). Therefore, when the casting speed of the actual model is 1.0 m/min, the physical casting speed should be 0.45 m/min. The actual speed is originated from Baosteel in China.

Combinational effect of SEN clogging rate and an external electromagnetic field on the flow pattern are investigated in this simulation. Four different SEN clogging rates are shown in Fig. 2. An external electromagnetic field is generated by a pair of stirrers, illustrated in Fig. 1(b). Each of them is comprised of one iron core and an arrangement of six coils. A three-phase power is supplied for this device. By supplying different external power, different EMS intensity can be obtained. The upper surface of the iron is located at the same height of the mercury surface, and the height of the iron is 30 mm. According to the same Magnetic interaction parameter and Magnetic shielding number, the ratio of magnetic flux density between the physical model and the actual model should be 1.7, and the ratio of frequency between them should be 17. Therefore, when the frequency of the actual model is 3 Hz, the corresponding frequency of the physical model is nearly 50 Hz. The turn number of every coil is 72. Some measurements of the magnetic flux density in the mold are shown in Fig. 3.

The flow velocity in the mold was measured by means of the Ultrasonic Doppler velocimetry (UDV) with the DOP2000 velocity-meter (model 2125, Signal Processing SA, Lausanne, Switzerland), equipped with 1 MHz transducers. This method is based on the pulse-echo technique and delivers instantaneous profiles of the velocity component projects onto the propagation direction of the ultrasonic
beam. As shown in Fig. 1(c), 28 sets of UDV probes are arranged at the quarter-plane of the mold. Two line arrays of five transducers are installed along the narrow face to measure the X-component velocity with a distance of 30 mm between the two adjacent sensors; and some other sensors are installed along the mold width to measure the Z-component velocity with a distance of 10 mm between the two adjacent sensors.

In order to gain a steady experimental condition, the experimental system should run for 10 min before the flow velocity measuring operation. For each probe, the measuring time is 120 s. Due to the limit of our current measured facility, all of the twenty-eight probes are measured one by one. After the experiment, these recorded data are converted into the form which could be identified by MATLAB. Time-averaged velocity from the data measured in 120 s was taken as the velocity for each measuring position. This produced a total of 28 independent velocity values that are used to reconstruct the flow field in the mold.

3. Results and Discussion

3.1. Effect of SEN Clogging Rate on the Flow in the Mold

3.1.1. Effect of SEN Clogging Rate on the Flow Field

Figures 4(a)–4(d) shows the 2D time-averaged velocity flow fields of the X-Z plane at $Y = -12.5$ mm with different SEN clogging rates. The velocity had been obtained by using an interpolation method based on the recorded horizontal and vertical velocity data. Figure 4(a) shows the time-averaged velocity field without clogging. Liquid metal leaves from the SEN ports as a strong jet with the maximum velocity of 0.1 m/s, travels and disperses in the mold, impinges on the narrow wall, splits into an upward flow and a downward flow along the narrow mold wall, and then forms an upper recirculating flow and an lower recirculating flow. The flow field in the mold is symmetrical. Figures 4(b)–4(d) displays the velocity fields with different clogging rates. Some observations from Fig. 4 are summarized below:

- For the case of 10% clogging rate, the flow field changes little, compared with the flow field without clogging. The symmetry of this flow is perfect.
- With the increase of the SEN clogging rate, the jet at the clogging side is restrained, while the jet at the non-clogging side is enhanced. The jet of the non-clogging side is much stronger than that of the clogging side. This may lead to variation in the mean velocities at the left and right sides, and the difference between them becomes obvious with the increase of the SEN clogging rate.
- The impinging point of the left jet declines with the increase in the clogging rate. Some small inclusions and bubbles will be entrapped into the lower region of the mold. It will make it difficult for the removal of them. However, the angle of the right jet changes little.
- The upper circulating flow at the clogging side becomes smaller with the increase of the SEN clogging rate. When the SEN clogging rate rises to 50%, it disappears completely, which goes against the removal of inclusions and the heat supply for the slag.

In a word, the symmetry of the flow field will be broken by the SEN clogging. It means that there is a difference of the distribution of the temperature field and the flow field between the clogging side and the non-clogging side, which will lower the slab quality because of the un-uniform growth of the initial solidification shell.

The velocity of the flow near the mold wall has a closely relationship with its washing intensity against the wall. The washing intensity will increase with the increase of the flow velocity. In order to evaluate the symmetry of the flow field with the SEN clogging, we have introduced a special index, named symmetrical index $S$. It is used to judge quantitatively whether the horizontal flow pattern is symmetrical or not. The definition of $S$ index is followed:
\[ S = \frac{1}{n} \sum_{i=1}^{n} \frac{\min(u_{Mi}, u_{Ni})}{\max(u_{Mi}, u_{Ni})} \] ................................. (4)

\[ u = \sqrt{u_x^2 + u_z^2} \] ................................. (5)

where \( u \) is the 2D velocity of the measured point, m/s; subscript Mi and Ni denote different measured points (shown in Fig. 5); and \( n = 18 \). The 2D velocity of each point can be calculated by Eq. (5), where \( u_x \) is the x-component velocity, m/s; and \( u_z \) is the z-component velocity, m/s. It should be mentioned that point Mi and point Ni are symmetrical about the center of SEN (such as M8 and N8, shown in Fig. 5). The integration path in the above equation is described as the four green dash lines (shown in Fig. 5). The SEN clogging will break the symmetry of the flow field in the mold (shown in Fig. 4), and EMS is often used to modify the flow field.\(^{24,25} \) The latter of this study is to investigate the optimization effect of EMS on the broken flow field due to the SEN clogging. Thus, the symmetry of the middle-plane of the iron core is chosen to describe the symmetry of the flow field, because the maximum of the magnetic flux density appears on this plane.\(^{34-36} \)

\( S \) index indicates the symmetry of the horizontal circulating flow about the geometric center of the mold. If the difference between \( u_{Mi} \) and \( u_{Ni} \) is small, it means that the washing intensity at the point M is almost equal to that at the point N. When \( S \) is close to 1, it implies that the symmetry of the horizontal circulating flow is perfect. When \( S \) is close to 0, it can be claimed that the symmetry of the

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Fig. 4. The 2D velocity field at the plane of \( Y = -12.5 \) mm with different SEN clogging rates. (a) Non-clogging, (b) Clogging rate: 10%, (c) Clogging rate: 25%, (d) Clogging rate: 50%.

Fig. 5. Schematic diagram EMF and the measured area. (Online version in color.)
flow is broken.

$S$ index decreases quickly with the increase of the SEN clogging rate, as shown in Fig. 6. When the SEN clogging rate raises from 0% to 50%, $S$ index will decrease from 1 to 0.325. It illustrates an approximate linear relation between the decrease of $S$ index and the increase of the SEN clogging rate. It implies that the symmetry of the flow field will be broken when the SEN clogging rate is high.

3.1.2. Effect of SEN Clogging Rate on the Free Surface Velocity

How to avoid slag entrapment in the mold is always a challenge for all the metallurgists. According to some recent researches, there are many mechanisms to account for slag entrapment, one of them is named Kelvin-Helmholtz instability. It can explain the effect of the drag force of the horizontal velocity acting on the molten slag, provoking its entrapment into the bulk of the molten steel. The corresponding critical velocity for slag entrapment can be defined by:

$$\Delta v^2 \geq 2\left(\frac{\rho_1 + \rho_2}{\rho_1 \rho_2}\right)\left(\frac{\gamma (\rho_2 - \rho_1)}{\rho_1 \rho_2}\right)^{1/2} \text{................. (6)}$$

where, $\rho_1$, $\rho_2$ are the density of the liquid slag (2 300 kg/m$^3$) and the liquid steel (7 000 kg/m$^3$), respectively; $\Delta v$ is the flow velocity difference near the steel-slag interface, m/s; and $\gamma$ is the steel-slag interface surface, 1.8 N/m. Based on this equation, the critical velocity difference for the actual model should be 0.326 m/s. According to Froude similarity principle, the critical velocity difference for our experiment should be 0.15 m/s. However, for our physical model, the two interference fluids are water (1 000 kg/m$^3$) and mercury (13 600 kg/m$^3$), respectively. There is a big difference in density between them. Water has little influence on the surface flow of mercury. Therefore, we treat the related critical velocity difference (0.15 m/s) as the critical velocity of slag entrapment for our experiment, which is also treated as the maximum free surface velocity.

In addition, B. G. Thomas and J. Kubota pointed out that the pinhole defects may occur frequently if the free surface velocity is too small. The heat supply for the steel-slag interface will be insufficient, resulting in the solidification of the liquid slag layer. They claimed that the free surface velocity should be larger than 0.1 m/s. Based on Froude similarity principle, the minimum free surface velocity for our physical experiment should be 0.045 m/s. Therefore, the reasonable free surface velocity should be ranged from 0.045 to 0.15 m/s for our experiment.

The velocity of the free surface flow with different SEN clogging rates are shown in Fig. 7. On one hand, when the SEN clogging rate is smaller than 50%, almost all of the mercury velocity data is located in the green shaded area, shown in Figs. 7(a)–7(c). It indicates that the mercury flow near the surface is acceptable. But, when the SEN clogging rate raises to 50%, some of the velocity profiles exceeds the shaded area, shown in Fig. 7(d). It implies that the high SEN clogging rate will lead to the unacceptable surface flow,
which may result in slag entrapment and pinhole defect. On the other hand, the velocity difference between the clogging side and the non-clogging side increases with the increase of the SEN clogging rate. It means that the asymmetry of the flow field will become obvious when the SEN clogging rate increases, which may lower the uniform development of the initial solidified shell.

3.2 Effect of EMS on the Flow with SEN Clogging in the Mold

3.2.1 Effect of EMS on the Flow Field without SEN Clogging

The SEN clogging will break the symmetry of the flow field in the mold, and the flow field has a significant influence on the slab quality. As an effective flow control technology, EMS has been applied to modify the flow field in the continuous casting mold for many years. Therefore, EMS is introduced to improve the asymmetrical flow field due to the SEN clogging in this study. In this section, some several experiments has been conducted to investigate the influence of EMS on the flow field without SEN clogging. When EMS is applied, an anticlockwise electromagnetic force (EMF) is generated, shown in Fig. 5. The four green dash lines denote the projections of the four measuring regions on the central plane of the stirrer. If the upper reversing flow direction is the same as the EMF direction, the region is defined as electromagnetic acceleration region (EMSA). Otherwise, it is defined as electromagnetic stabilization region (EMSL). Each case has two EMSA sides and two EMSL sides.

Figure 8 reveals the 2D time-averaged velocity field on the plane \( Y = -12.5 \) mm with 60A-EMS and non-clogging. When EMS is applied, the flow pattern has been completely changed. Both the two down-inclined jets and the upper recirculating flow at the EMSA side disappear, compared with the flow pattern in Fig. 4(a). Due to the interaction between the inertia force of the upper recirculating flow and the electromagnetic force, the flow at the EMSA side is enhanced, while the flow at the EMSL side is weakened. At the same time, the upper flow near free surface is stimulated. At the EMSA side, the flow tends to flow to the mold narrow face. But, a horizontal flow from the SEN to the narrow face appears in the middle region of the EMSL side. Some flow directions are illustrated in Fig. 8.

![Fig. 8. The 2D velocity field at the plane of \( Y = -12.5 \) mm with 60A-EMS and non-clogging.](image)

![Fig. 9. The 2D velocity filed with 60A-EMS and 50% SEN clogging rate. (a) Plane of \( Y = 12.5 \) mm, (b) Plane of \( Y = -12.5 \) mm.](image)
3.2.2. Effect of EMS on the Flow Field with SEN Clogging Rate

When the SEN clogging rate is low (10% and 25%), the flow field in the mold is symmetrical. But, when it raises to 50%, the symmetry of the flow field is broken. It may lower the slab quality. Thus, we need to investigate whether EMS can optimize the asymmetrical flow field with 50% SEN clogging rate or not. Figure 9 depicts the 2D velocity field with 60A-EMS and 50% SEN clogging rate. Figures 9(a) and 9(b) show the velocity field on the planes of \( Y = -12.5 \) mm and \( Y = 12.5 \) mm, respectively. For the case of the EMSA side, the liquid mercury tends to flow from the SEN to the mold narrow face. As for the EMSL side, the flow is complicated. In the upper domain, the mercury inclines to upward. In the middle domain, it tends to flow from the SEN to the mold narrow face. In the lower domain, a lower recirculating flow tendency can be seen. The flow field structures on the plane of \( Y = -12.5 \) mm and \( Y = 12.5 \) mm are almost central symmetry about the SEN. It indicates that EMS can modify the central symmetry of the flow field due to the SEN clogging, which may improving the slab product quality.

3.2.3. Effect of EMS on the Symmetry of the Flow Field

\( S \) index with different SEN clogging rates and different EMS currents are shown in Fig. 10. Without EMS, \( S \) index decreases obviously with the increase of the SEN clogging rate, as shown in Fig. 6. When EMS is applied, the symmetry of the flow field with the SEN clogging has been improved. For the case of 50% clogging rate, when 40A-EMS is applied, \( S \) index increases from 0.325 to 0.577. When 60A-EMS is applied, \( S \) index increases from 0.577 to 0.774. It indicates that EMS can improve the symmetry of the flow field, and \( S \) index will increase with the increase of the EMS current. However, when the SEN clogging rate is high (50%), EMS cannot completely remove the asymmetry of the flow field. Above all, EMS can optimize the asymmetrical flow field due to the SEN clogging, but the optimization effect doesn’t have an approximate linear relationship with the increase of EMS current. In other words, when the degree of SEN clogging is high (50%), neither 40A EMS nor 60A EMS can remove the asymmetrical flow filed in the mold completely.

3.2.4. Effect of EMS on the Free Surface Velocity with Different SEN Clogging Rates

EMS has significantly influence on the free surface flow
in the mold. The free surface velocity with different SEN clogging rates and different EMS currents are shown in Fig. 11. The free surface flow is reasonable, if the flow velocity is within the green shadow region. Based on the free velocity criterion (section 3.1.2), when 40A-EMS is applied, almost all of the free surface flow are acceptable, except for part of the surface flow with 50% SEN clogging rate. However, when 60A-EMS is applied, the free surface flow cannot be accepted. Because the application of EMS will stimulate the activity of the free surface flow, thereby accelerating the free surface flow. It may result in slag entrapment. This indicates that once the EMS current is too large, the free surface flow will be unacceptable. It may lower the slab quality.

The SEN clogging will break the symmetry of the flow field and lead to the unreasonable free surface velocity. The flow at the non-clogging side is much stronger than that at the clogging side. With the increase of the SEN clogging rate, the asymmetry of the flow field will decrease. In this study, EMS is introduced to modify the broken flow field in the mold. When the SEN clogging rate is not too high (<50%), the symmetry of the flow field will be improved by EMS. With the increase of the EMS current, the optimization effect will be more obvious. It may promote the development of the uniform initial solidified shell. But, EMS will also stimulate the free surface velocity, leading to slag entrapment. Therefore, 40A-EMS is suggested to optimize the unfavorable flow field due to the SEN clogging in this study.

4. Conclusions

A 1:5 scaled physical model was conducted using mercury and the flow velocity was measured by UDV. Both the effect of the SEN clogging rate on the flow field and the influence of EMS on the adverse flow due to the SEN clogging were discussed. Moreover, an optimal EMS current was suggested. Some following conclusions can be drawn from this study:

(1) SEN clogging will break the symmetry of the flow field in the mold. The flow at the non-clogging side is much stronger than that at the clogging side.

(2) $S$ index is proposed to judge whether the horizontal flow is symmetrical or not. With the increase of the SEN clogging rate, $S$ index decreases quickly.

(3) EMS can improve the symmetry of the flow field, when the SEN clogging rate is under 50%. With the increase of the EMS current, the optimization effect is obvious. However, when the SEN clogging rate raises to 50%, the asymmetrical phenomena cannot be removed completely by EMS.

(4) Although EMS can improve the symmetry of the flow field, the free surface flow will be also stimulated by EMS. Thus, the optimal EMS current for improving the broken flow field with the SEN clogging is 40 A in this study.

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