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ANALYSIS OF THE EFFECTS OF AN ELECTROMAGNETIC BRAKE(EMBR) ON FLOW BEHAVIORS IN THE LARGE SLAB CONTINUOUS CASTING MOLD

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In the present paper, molten steel flow in the submerged entry nozzle (SEN) and mold cavity of large slab continuous caster in both environments (with EMBR and without EMBR) were investigated with the method of numerical simulation. In addition, the impacts of electromagnetic brake (EMBR) on molten steel flow and meniscus fluctuation were discussed while the bath meniscus fluctuation was monitored in a steel plant. Computation results were compared with experimental findings of the factory and it is verified that EMBR can be an efficient technology to control liquid steel flow behaviors in the large slab continuous casting mold.

Key words: steel, large slab continuous caster, electromagnetic brake, fluid flow, numerical simulation

INTRODUCTION

As we all know, mold is considered as the heart of continuous caster. Molten steel with such large flux injecting from the submerged entry nozzle (SEN) to the mold may lead to serious problems, such as unmanageable turbulence, meniscus fluctuation, inclusions entrapment, etc. Which are closely related to steel quality in continuous casting process [1], especially in large slab continuous casting. In more recent work[2,3], optimizing the structure of SEN is studied to control molten flow in the mold.

Flow control mold electromagnetic brake (FC-mold EMBR) [4] is a non-contacting way to control fluid flow of liquid steel from the nozzle ports and meniscus fluctuations. This type of EMBR includes two rectangular magnets across each wide copper plate of mold. One is located at the meniscus, and the other is located beneath the SEN ports. Static electromagnetic fields induce current in the conducting liquid steel, which can generate forces that oppose the flow directly. So FC-mold EMBR can overcome or eliminate these problems by suppressing and redistributing molten steel flow in the mold.

In the current study, fluid flow behavior and meniscus fluctuation of large slab casting mold in a steel plant are numerical simulated. At last, the testing result is analyzed with the basis of the testing data and curve on spot.

SLAB CASTER DESCRIPTION

Table 1 lists parameters of large slab mold in a steel plant. The object of the study is an adjustable mold designed for the continuous casting of large slabs intended for wide-thick plate, as shown in Figure 1.

Table 1 **Parameters of slab mold and SEN**

Parameters	Values
Number of slab mold	2
Mold width / mm	2 150
Mold length / mm	900
Mold thickness / mm	230
Meniscus level below top of mold / mm	80
Casting speed / m · min^{-1}	1,6
Depth of SEN / mm	200
Total height of SEN / mm	920

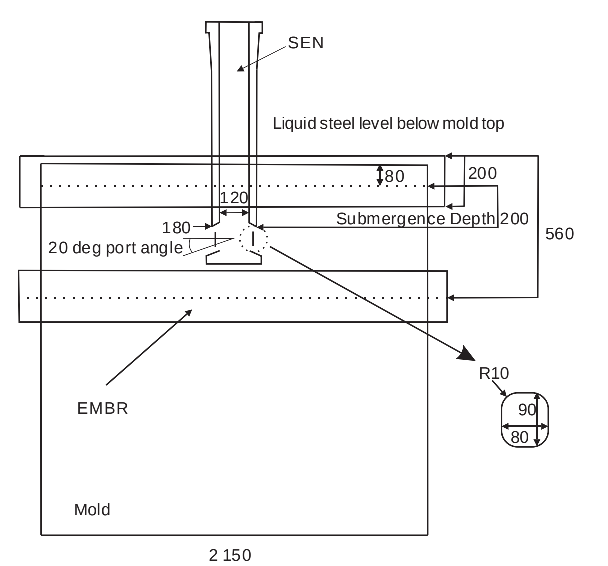

Figure 1 Schematic of the industrial slab caster with two rectangles showing the location of FC-mold electromagnetic brake (all dimensions in mm)

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In order to further control the turbulence of liquid steel in the mold, geometrical structure of SEN is also designed to bifurcated outlets accordingly, the bottom shape of the SEN inside changed from convex angle to concave surface, and the port angle was 20 deg.

COMPUTATIONAL MODEL

Within the current study, the commercial fluid flow software CFX is used to numerically simulate the interaction between the mold flow and the external magnetic field, which is based on a three-dimensional (3-D) finite-volume method. The Reynolds-averaged Navier-Stokes (RANS) model of turbulent fluid flow is used to simulate the time averaged flow pattern in large slab mold with FC-EMBR. The equation of continuity, momentum equation and Maxwell's equation and other details are available elsewhere[5-7].

The meniscus height (H_M) is approximately calculated, as in Reference [8, 9], using

$$H_M = \frac{P_{static} - \overline{P}_{static}}{(\rho_{steel} - \rho_{slag}) \times g} \quad (1)$$

Where P_{static} is static pressure at each point, $\vec{P}_{static}$ is the average static pressure over the top surface of mold, ρ_{steel} is steel density, ρ_{slag} is slag density, and g is the gravitational acceleration.

Additional details and simulation parameters are given in Table 2. The meshes of mold and SEN are comprised of 2,4×10^5 hexahedral cells. At the inlet, the mold cavity is served by the SEN, and nozzle inlet velocity determined by casting speed is fixed for mass continuity. Pressure is set to be atmospheric. The turbulent kinetic energy and its dissipation rate at the inlet are obtained by using the semi-empirical relations as follows:

$$k = 0.01u_{in}^2 \quad (2)$$

$$\varepsilon = \frac{k^{3/2}}{d_{nozzle}} \quad (3)$$

Where d_{nozzle} is the hydraulic diameter of the nozzle.

Table 2 **Simulation parameters**

Parameters	Values
Mass flow rate / $t \cdot min^{-1}$	5,5
Density(steel) / $kg \cdot m^{-3}$	7 020
Density(slag) / $kg \cdot m^{-3}$	3 100
Conductivity of liquid steel / $(\Omega m)^{-1}$	7,14×10^5
Kinematic viscosity of liquid steel / $m^{-2} \cdot s^{-1}$	8,6×10^5
Viscosity (μ) / $kg \cdot m^{-1} \cdot s^{-1}$	2,16×10^{-3}
Gravity / $m \cdot s^{-2}$	9,81
The maximum of magnetic flux density / T	0,3

The calculated Lorentz force using the electromagnetic equations is added into the momentum equations as a source term. The free surface and symmetry plane are set to adiabatic wall boundary condition with zero normal component of electric potential, and a no-slip boundary condition is employed. A uniform velocity is determined at the inlet opening based on the required mass flow rate, and the other details are available elsewhere [8-10].

Figure 2 Streamline of molten steel in half SEN: (a) without EMBR; (b) with EMBR

RESULTS AND DISCUSSIONS

Effects of EMBR on flow pattern of SEN

Figure 2 gives streamline of molten steel in half-SEN. From Figure 2, it can be seen that after applying EMBR, the molten steel flow pattern around SEN has significant changes. Without EMBR, the molten steel is poured from the SEN along the direction of the ports angle, as shown in Figure 2a. After applying EMBR, the electromagnetic force in opposite directions causes the molten steel stream to bend down and inward in the vertical direction, as shown in Figure 2b.

Effects of EMBR on flow pattern in mold

In the large-slab continuous casting process, the mass flow rate of casting is generally approximately 5,5 t/ min which is much larger than the mass flow rate in a conventional slab casting process. Figure 3 and 4 present streamline and velocity field in the large slab continuous casting mold, respectively, where significant changes of the flow pattern from EMBR impact are shown, as mentioned in Reference [8-10]. Without EMBR, the molten steel with such high-speed injecting from SEN to the mold may create a typical double-whirlpool flow pattern. The powerful whirlpool penetrates deep into the lower mold region, where the steel flow speed is greater as it moves toward mold narrow face (up to ~0,52 m/s), as shown in Figure 3a and Figure 4a. Whereas the little whirlpool generates a re-

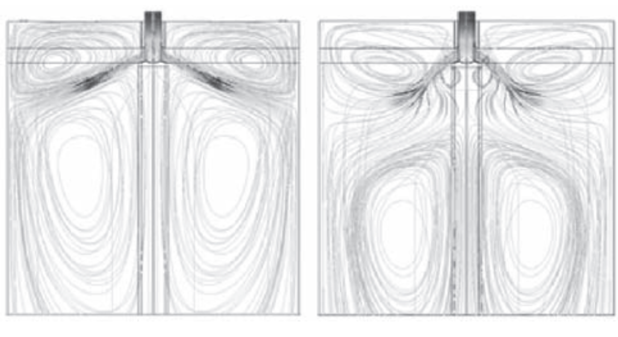

Figure 3 Streamline on mold wide face centerplane: (a) without EMBR; (b) with EMBR

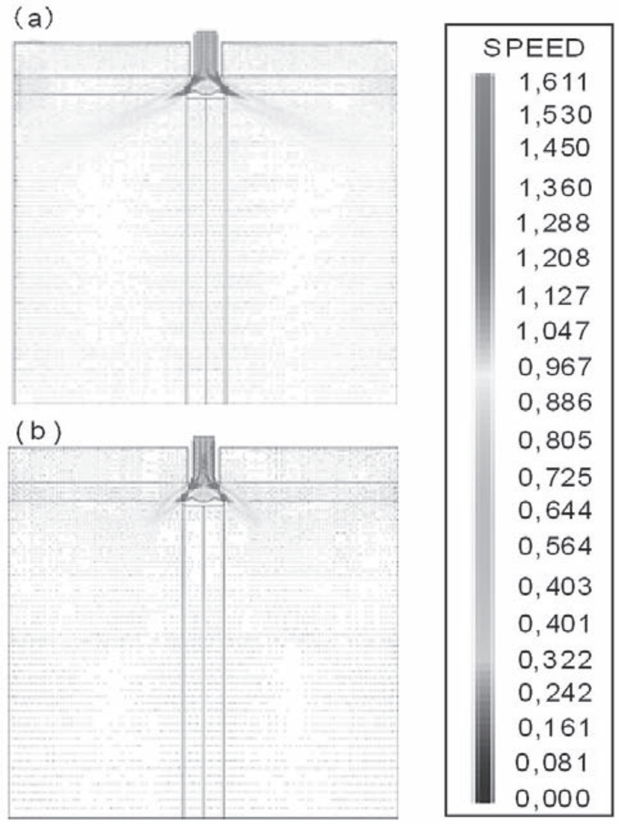

Figure 4 Velocity field on mold wide face centerplane: (a) without EMBR; (b) with EMBR

versed flow around the jet flow and SEN face in the upper mold region gets sufficient development. A lot of high-speed streams are concentrating near the bath surface (up to ~0,44 m/s), which is sensitive to cause problems, such as strong fluctuation, entrapment of inclusions, *etc*. as shown in Figure 3a and Figure 4a.

After applying EMBR, the typical double-whirlpool flow pattern is broken and transformed into a new and more stable flow structure, which displays that velocity field becomes more homogeneous, as shown in Figure 3b and Figure 4b. As mentioned before, steel flow velocity and direction injected from SEN change greatly because of the Lorentz force. The high speed streams are spread more thinly near narrow face (up to ~0,12 m/s) and bath surface (up to ~0,08 m/s) compared with the No-EMBR condition, as shown in Figure 3b and Figure 4b.

Effects of EMBR on meniscus fluctuation

In order to verify the validity of the simulation and the function of EMBR, the control system of molten steel level was used to measure bath meniscus fluctuation for the No-EMBR (and with EMBR) condition. A measurement data of 40 minutes in length during large slab continuous casting production (or in numerical simulation) was randomly selected to calculate ΔH_{wave}, which is the wave height difference between the maximum and the minimum values. The measured and simulated ΔH_{wave} are compared in Figure 5.

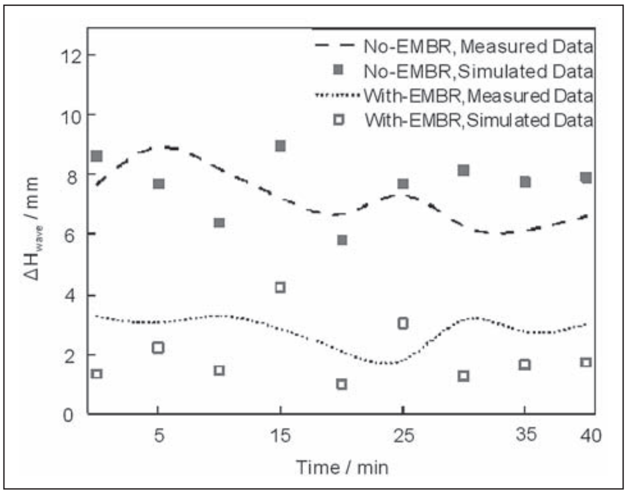

Figure 5 Comparison of calculated ΔH_{wave}

From Figure 5, it can be seen that the numerical simulation is an effective research method, with which the result is similar to that measured by equipment. Without EMBR, ΔH_{wave} of both measured data and simulated data are above 5 mm (the upper limit of safety production), the maximum values of the simulation and measurement are 8,81 mm and 9,07 mm respectively. After applying EMBR, the two values above drop to 3,28 mm and 4,22 mm, which are less than 5 mm. After a comparison, using EMBR controlling technology has an obvious positive effect to safety and security in large slab continuous casting.

CONCLUSIONS

Fluid flow behavior in the large slab continuous casting nozzle and mold (with and without EMBR) were investigated using CFX, and the simulated results were verified by the wave height measurement in a steel plant. Under EMBR circumstances, the steel flow pattern changed significantly, flow velocity and direction injected from SEN change greatly. The high speed streams are spread more thinly near narrow face and bath surface compared because of EMBR. For the bath meniscus fluctuation, the wave height difference can be well controlled under the upper limit of safety production (5 mm).

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Note: The responsible translator for English language is X.T. Yin - University of Science and Technology Liaoning, China