Study of interfacial fluctuation of molten steel and liquid slag in continuous casting mould with vertical electromagnetic brake

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Abstract: A 3-D mathematical model has been developed to investigate the behavior of molten steel and liquid slag interfacial fluctuation considering the effects of vertical electromagnetic brake (V-EMBr) in slab continuous casting mold. The Volume of fluid (VOF) model is used to describe the interfacial behavior of molten steel and liquid slag with different current density of coils. The results show that the V-EMBr can effectively reduce the interfacial fluctuation caused by the changing of nozzle submergence depth and port angle For a given casting speed, as increasing of magnetic induction intensity the height of interfacial fluctuation (the maximum value of wave height) is significantly reduced and its position gradually approached to the narrow face of the mold, that is beneficial to reduce the possibility of mold flux entrapment.

Key words: vertical electromagnetic brake; VOF model; interfacial fluctuation; continuous casting mold

Introduction

In the process of continuous casting, the phenomenon of mold flux entrapment is easily to be caused with the increasing of casting speed. The developed of electromagnetic brake technique can effective control the flow of molten steel, stable the fluctuation of steel/slag interfacial to reduce the probability of mold flux entrapment and promotes the removal of inclusions, thus both the surface and internal quality of slab can be improved. However the effect of traditional electromagnetic brake is obviously influenced by process and electromagnetic parameters, such as SEN port angle, distance between SEN port and magnetic pole position (Level Magnetic Field) [1], current density match of upper and lower magnetic pole (FC-Mold) [2] and so on. An unreasonable parameters match will lead to an unexpected brake effect for traditional electromagnetic brake.

In this study, a new type electromagnetic brake device that called vertical electromagnetic brake (V-EMBr) is proposed to control the molten steel and liquid slag interfacial fluctuation in slab continuous casting process, and the effect of different current density of coils on the behavior of molten steel and liquid slag interfacial fluctuation in V-EMBr mold is studied using a mathematical model.

Mathematical Model

In order to ease the complexity of establishing mathematical model, certain assumptions were made in this model. The molten steel flow in the mold is a 3D transient state, incompressible and viscosity flow process, the effects of solidification shell and oscillation of the mold on the molten steel flow are ignored, only the liquid slag layer is considered, other state slag layers are ignored.

Fluid flow equations

Continuity equation:

$$\nabla \cdot \rho\vec{u}=0 \tag{1}$$

Momentum equation:

$$\rho\left[\frac{\partial\vec{u}}{\partial t}+(\vec{u}\cdot\nabla)\,\vec{u}\right]=-\nabla p+\mu_{\text{eff}}\nabla^2\vec{u}+\rho\vec{g}+\vec{F}_{\text{m}} \tag{2}$$

where, $\rho = \rho_{slag}(1-\alpha_{steel}) + \rho_{steel}\alpha_{steel}$, kg/m3; p is pressure, Pa; μ_{eff} is effective viscosity which is determined by the standard *k-ε* two–equation turbulence model as proposed by Launder and Spalding[3]; $\vec{F}_m$ is induced electromagnetic force components, N/m^3.

Interface fluctuation model equation

In this study, VOF model is used to describe the interfacial behavior of molten steel and liquid slag. The volume fraction of molten steel should satisfy the flowing continuous function:

$$\frac{\partial \alpha_{steel}}{\partial t} + \vec{u}\cdot\nabla\alpha_{steel} = 0 \tag{3}$$

Where t is time, s; Volume fraction α_{steel} is volume fraction of steel; $\vec{u}$ is vector of velocity, m/s.

Electromagnetic field equations

The induced current density equation is given by:

$$\vec{j} = \frac{1}{\mu}\nabla\times\vec{B} \tag{4}$$

With $\vec{B} = \vec{B}_0 + \vec{b}$, $\vec{B}_0$ is externally imposed magnetic field; $\vec{b}$ is induced magnetic field due to fluid motion. The induced magnetic field $\vec{b}$ can be solved by flowing equation [4]:

$$\frac{\partial \vec{b}}{\partial t} + (\vec{u}\cdot\nabla)\vec{b} = \frac{1}{\mu\sigma}\nabla^2\vec{b} + ((\vec{B}_0+\vec{b})\cdot\nabla)\vec{u} - (\vec{u}\cdot\nabla)\vec{B}_0 \tag{5}$$

Electromagnetic force equation:

$$\vec{F} = \vec{j}\times\vec{B} \tag{6}$$

Where t is time, s; $\vec{j}$ is the current density; σ is the electrical conductivity of the steel, S/m; $\vec{u}$ is vector of velocity, m/s; $\vec{F}$ is induced electromagnetic force, N/m^3.

Boundary conditions and process of solution

1) Inlet velocity: The inlet velocity is determined by steel flow rate equilibrium, the initial values of *k–ε* at the inlet are: $k_{inlet} = 0.01u_{inlet}^2$, $\varepsilon_{inlet} = k_{inlet}^{1.5}/(d_{inlet}/2)$. d_{inlet} is the diameter of the SEN.
2) Wall: Velocity and the current density components normal to the wall are set to zero and all walls are set to be electrically insulated.
3) Symmetry faces: The velocity and the current density components normal to the symmetry faces are set to zero and all other variables normal gradients are set to zero.
4) Outlet: At the outlet of the mold, normal gradients of all the variables are set to zero.

Schematics of geometrical model and hexahedral structured mesh of fluid zone are shown in Fig.1, and the detailed process and simulation parameters are shown in Table 1. The scalar magnetic potential method is used to solve the electromagnetic field in fluid zone for different current intensity of coils with commercial software ANSYS. The coupling calculation of magnetic field and flow field is performed in FLUENT computational fluid dynamics software. The pressure-velocity coupling algorithm is PISO algorithm. In order to obtain the most accurate interface shape, the geometric reconstruction approach is adopted, and the continuum surface force model (CSF) is employed to describe the effect of surface tension [5].

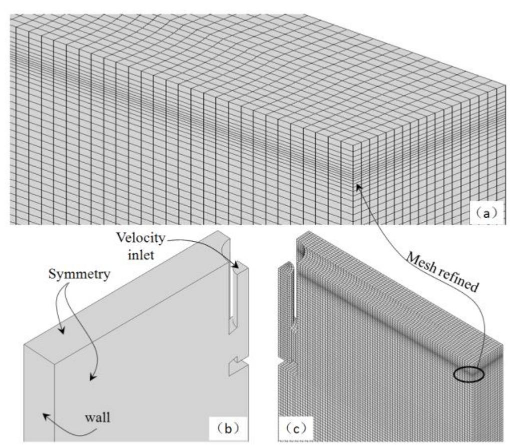


Fig. 1: Schematics of geometrical model (a) Refined mesh; (b) Fluid zone; (c) Hexahedral structured mesh of fluid zone

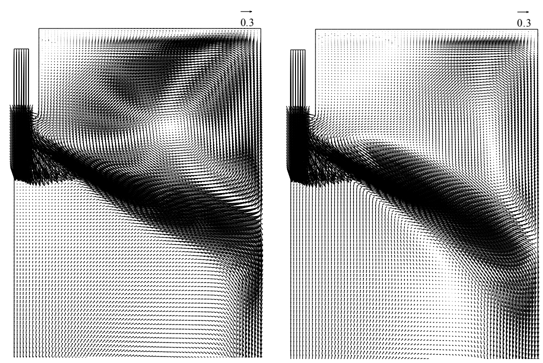
Table 1 Process and physical parameters

Parameters	Value	Parameters	Value
Mold size, mm	1200 x 200	SEN submergence depth, mm	180
SEN port angle, °	-15	Casting speed, m/min	1.8
Molten steel density, kg/m^3	7200	Molten steel viscosity, Pa·s	0.006
Liquid slag density, kg/m^3	2700	Liquid slag viscosity, Pa·s	0.2
Thickness of Slag layer, mm	30	Tension coefficient, N/m	1.6
Contact angle, °	60	Current density, A	0, 100, 200, 350
Electric conductivity, S/m	7.14 x 10^5	Magnetic conductivity, H/m	1.257 x 10^{-6}

Results and Discussion

Flow characteristic in mold with vertical electromagnetic brake

Fig. 2 shows the velocity vectors at half thickness symmetric plane of mold with and without V-EMBr. Without V-EMBr applied, the jet flow of molten steel impinges on the narrow face of the mold with high impinging intensity and forms two opposite directional re-circulation zone. The value of wave height is increased because of the strong upward flow and the maximum value ups to 17.9mm. While with V-EMBr applied, the magnetic field successfully suppressed the flow intensity and velocity of molten steel in upward backflow zone and meniscus zone which cause the value of wave height decreased from 17.9mm to 8.43mm. Obviously it is mainly because of the magnetic field which produced by V-EMBr can cover upward backflow zone and meniscus zone at the same time. Therefore, the flow intensity and velocity of molten steel in different zones are successfully suppressed by V-EMBr.



Without V-EMBr With V-EMBr

Fig. 2: Velocity vectors at half thickness symmetric plane with and without V-EMBr

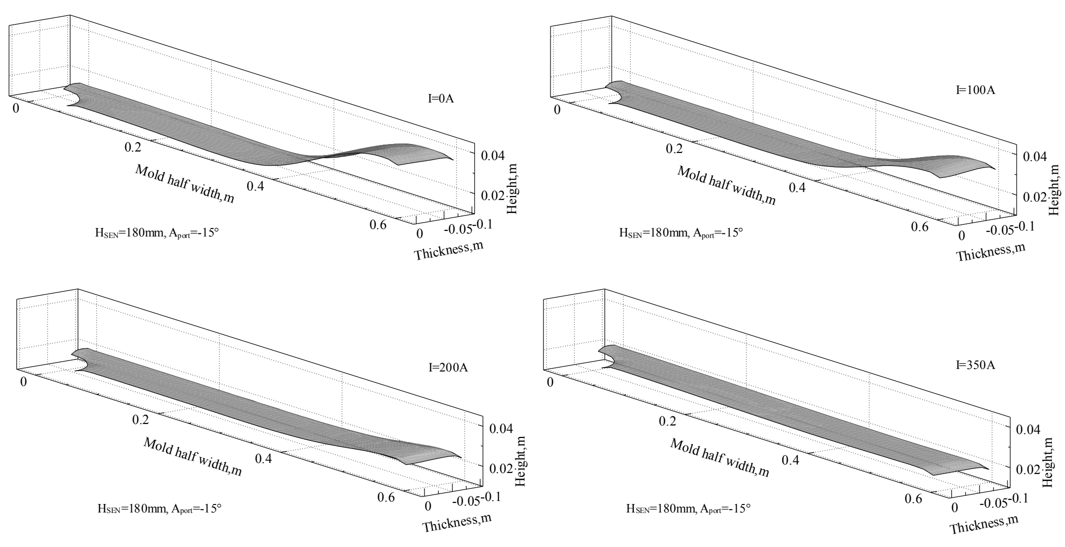


Fig. 3: Steel/slag interface profiles with different current density

Effect of current density on behavior of steel/slag interface profile

Fig. 3 shows the steel/slag interface profiles with different current density in vertical EMBr mold. It can be found that the wave height can be obviously depressed by V-EMBr, the value of wave height decreases with the increasing of current density, which the maximum value of wave height decreases from17.9mm (without V-EMBr) to 1.2mm (current density is 350A). It also can be seen from Fig. 3 that the position (along X axis direction) with maximum value of wave height gradually approached to the narrow face of the mold from 33mm to the narrow face reduce to 22mm with the increasing of current density. The maximum value of wave height approached to the narrow face is beneficial to promote the melting of slag and to reduce the possibility of mold flux entrapment.

Effect of current density on surface velocity and vertical velocity

Fig. 4 shows the surface velocity at steel/slag interface and vertical velocity Vy near narrow face of mold with different current density. We can see from Fig. 4(a), the surface velocity at steel/slag interface obviously decreased with the increasing of current density, and the maximum value of surface velocity decreased from 0.23m/s to 0.025m/s. The suppression effect of V-EMBr (current density is 350A) on the surface velocity at steel/slag interface is close to the suppression effect of FC-Mold [6]. Fig. 4(b) shows the vertical velocity of molten steel nearby the narrow face of mold. It can be seen that the value of velocity vector in the vicinity of impact point are all declined due to the V-EMBr applied. The value of vertical velocity decreased from 0.3m/s to 0.18m/s in the upward backflow zone. The reduction of the vertical velocity in upward backflow zone is helpful to decrease the height of molten steel and liquid slag interfacial fluctuation and even to reduce the possibility of mold flux entrapment.

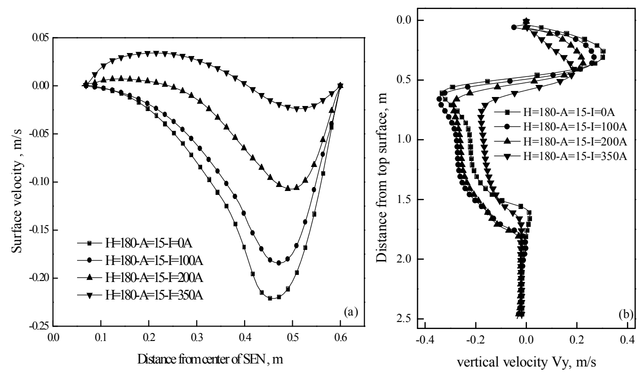


Fig. 4: Surface velocity at steel/slag interface and vertical velocity Vy near narrow face of mold

Conclusions

1） The velocity of molten steel in upward backflow zone can be obviously suppressed by V-EMBr.

2） The use of V-EMBr can decline the height of wave with a low current density (350A), while the brake effect of V-EMBr is closed to FC-Mold with a high current density.

3） For given SEN submerged depth, casting speed and SEN port angle, the brake effect of V-EMBr is enhanced with the increasing of current density of coils. With V-EMBr applied, not only can reduce the surface velocity, but also can reduce vertical velocity near the narrow side of mold.

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