Numerical simulation on level fluctuation in bloom casting mold with electromagnetic stirring

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Abstract. Based on a 380mm × 280mm bloom caster mold, the level fluctuation of steel-slag interface in the mold was simulated by the VOF model of commercial software Fluent. The effects of current intensity and frequency of EMS (electromagnetic stirring) on the level fluctuation in the mold were studied. The results show that whether or not with EMS, the maximum level fluctuation site of the mold occurs in the vicinity of the submerged entry nozzle. Compared with casting without EMS, molten steel flows horizontally rotatably under the action of the electromagnetic force by electromagnetic stirring, so the impact depth of molten steel decreases, then the level fluctuation slightly reduces, and the maximum level fluctuation value in the wide direction and the narrow direction of the mold, reduce from 4.24mm and 4.14mm to 4.04mm and 3.73mm respectively. With increasing intensity and frequency of current, the mold level fluctuation rises and the distribution uniformity of the level fluctuating amplitude worsens. The maximum level fluctuation enlarges by 0.18mm with raising the current intensity from 450A to 550A, but it enlarges by 0.79mm with 600A current intensity. The maximum level fluctuation enlarges by 0.15mm with raising the current frequency from 1.5Hz to 2.0Hz, but it quickly enlarges by 0.78mm with 2.5Hz current frequency. When the current strength and frequency are not more than 550A and 2.0Hz, level fluctuations are 4.00mm or less, which can meet requirements for controlling the bloom surface quality.

1. Introduction

Electromagnetic stirring (EMS) is widely used for its metallurgical effect on inclusion removal, the elimination of subsurface bubbles, reducing central segregation and improvement of central equiaxed grains. In recent years, the EMS technology has been researched by a number of metallurgical scholars. Liang Zhou et al [1-3] have tested the magnetic field of M-EMS by using a Gauss meter, qualitatively analysed the characteristics of the electromagnetic field, and the relationships of current intensity with stirring speed, molten steel flow, fluid velocity distribution were discussed. Miaoyong Zhu et al [4] have simulated the three-dimensional flow field and temperature field of a bloom mold, researched the influence of stirring intensity on the flow field and temperature field of molten steel, but dealt with the mold free surface as a plane of symmetry or no shear stress free wall. Furthermore, research on the level fluctuation was not done. At present, studies of the free surface mostly focuses on slab molds [5,6], and research on bloom molds is rarely reported [7,8]. Jiaquan Zhang et al [7] have studied the level fluctuation of the free surface under different nozzle hole angles by building a

steel-slag-gas three phase free surface, but the influence of EMS was not considered. In the present work, the steel-slag-gas three phase free surface model was built by VOF multiphase flow model. The influence of EMS parameters on level fluctuation of the mold was studied. Thus the proper EMS parameters could be found to guide production.

2. Calculation methods and conditions

2.1. Assumptions
The actual fluid flow in mold is a complicated physical and chemical process. The principal assumptions are made in the modelling as follows:

- Molten steel are treated as incompressible viscous fluids with the physical properties as constants.
- A solidified shell doesn't exist in mold.
- The cover slag is regarded totally as liquid in mold.
- The influence of mold oscillation on the flow field in mold is neglected.

2.2. Governing equations
Basic conservation equations for molten steel flow include the mass conservation equation and the momentum conservation equation. The two-equation k-ε model is adopted as a turbulence model [7, 9, 10].

The SOLA-VOF method was used to simulate the mold free surface (air-powder-steel interface), and the geometric reconstruction method was applied to track the free surface fluctuations. The volume function of the free surface boundary F(x, y, z, t) is defined as follows [11, 12]:

$$F = \begin{cases} 1 & \text{volume is fully filled} \\ 0 \to 1 & \text{volume is filled in part} \\ 0 & \text{volume is empty} \end{cases} \tag{1}$$

F (x, y, z, t) satisfies the Volume function equation:

$$\frac{\partial F_i}{\partial t} + \left[\frac{\partial}{\partial x_i} (F_i \cdot u_i) \right] = 0 \tag{2}$$

where, u_i is the velocity components in x, y and z direction (m/s); t is time (s).

2.3. Boundary conditions
The boundary conditions of the model can be determined as follows:

- Inlet boundary condition: The top cross section of the submerged entry nozzle is set as the inlet. Molten steel injection rate is calculated by the casting speed.
- Outlet boundary condition: The bottom cross section of the mold is set as the outlet, which is the speed outlet boundary.
- Mold wall: The velocity component vertical to the wall is zero. Velocity component, pressure, k and ε parallel to the wall are set to the no-slip boundary condition. In the boundary layer nearby the mold wall, the fluid parallel to the wall is calculated by the wall function.
- The top surface of the mold is set to the atmospheric pressure inlet. The material of the inlet is air.
- Each phase initialization: the space below 100mm from top of the mold is the molten steel. The molten steel is covered by a 10mm thick layer powder. The space above the powder is air.

2.4. Calculation conditions and solving method

The size of mold was 380mm×280mm×800mm, and the computational domain height was 1800mm for eliminating the effect of the lower mold exports on flow field. A submerged entry nozzle is set at the centre of the mold. The calculation and operating conditions of the caster are listed in table 1.

The time averaged electromagnetic force data F_X, F_Y, which were simulated by electromagnetic stirring, were loaded on the momentum equation in X, Y directions using the UDF program, so that the molten steel in the mold produced a cross-sectional tangential velocity V_X, V_Y in order to simulate the mold by EMS, as shown in figure 1.

Table 1. Main process parameters.

| Physical property	Value
The type of nozzle	Four-hole
Nozzle diameter, mm	81
Insertion depth of nozzle, mm	210
Casting speed, m/min	0.6
Molten steel density, kg/m^3	7100
Molten steel viscosity, Pa·s	0.0055
Molten Slag density, kg/m^3	2700
Molten Slag viscosity, Pa·s	0.41
Air density, kg/m^3	1.225
Air viscosity, Pa·s	$1.79×10^{-5}$
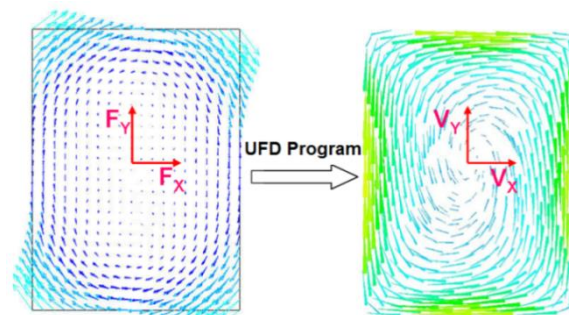
Figure 1. Electromagnetic force vector field (a) and flow field vector field (b) in the cross-section of the mold.

3. Results and Discussions

3.1. Comparison of level fluctuation with EMS and without EMS

The comparison of three dimensional flow field distributions of strand flow from the nozzle in the mold with EMS and without EMS is shown in figure 2.

As can be seen in figure 2: without EMS, the impact depth of molten steel is larger after the outlet of the molten steel, and part of the steel flows upwards to shock the powder and cause disturbance of the powder layer. After adding EMS, most of the steel spirals downwards along the mold axis under the electromagnetic force, then the impact depth of the molten steel is greatly reduced, and the small part of the steel that moves upward was weakened by the rotating electromagnetic force, so that longitudinal impact on the powder layer was decreased.

(a)   (b)
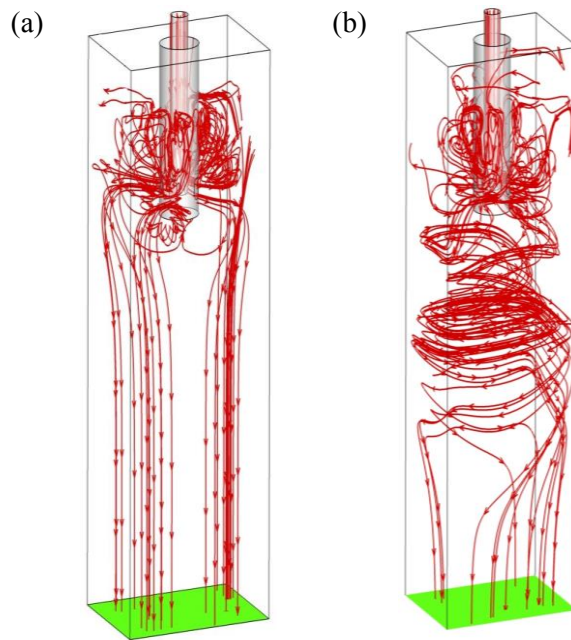
Figure 2. The comparison of three dimensional flow field distribution of mold steel flow without (a) and with (b) EMS.

(a)   (b)
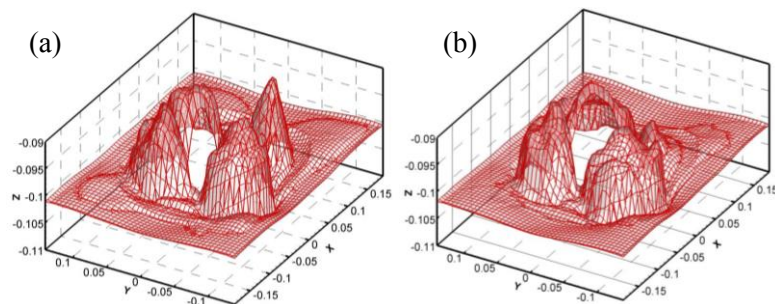
Figure 3. The comparison of three dimensional level fluctuation in the mold without (a) and with (b) EMS.
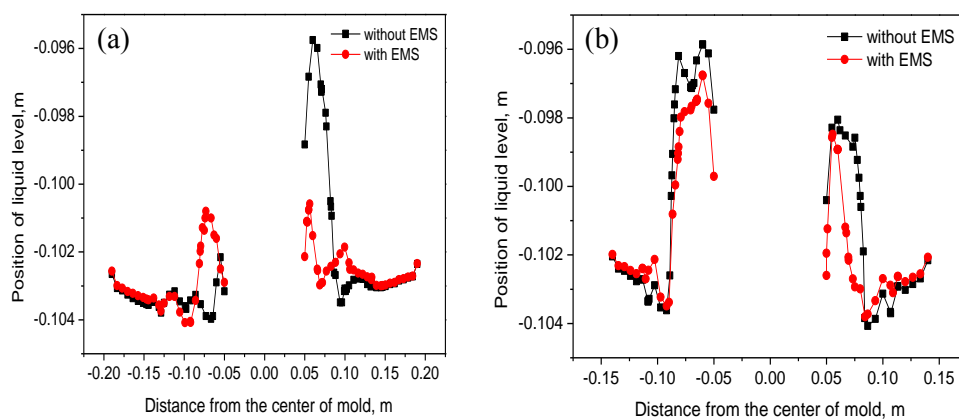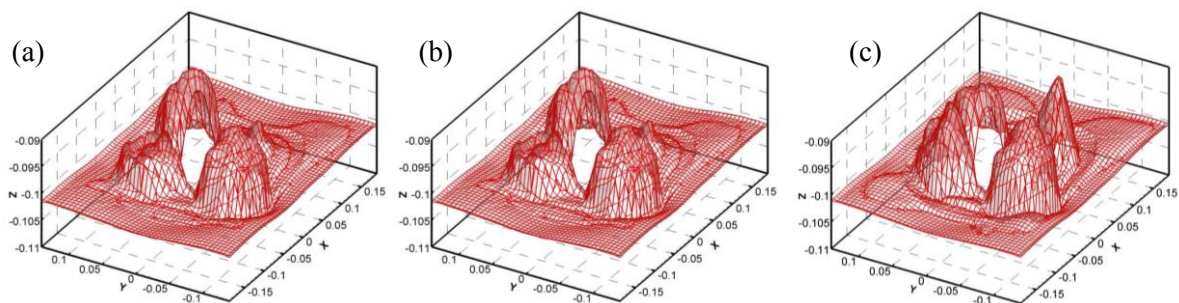

Figure 4. The level fluctuation value distributions in the wide direction (a) and the narrow direction (b) of the mold with and without EMS.

The comparison of three-dimensional time-averaged level fluctuation with and without EMS is presented in figure 3. The comparison of free surface level fluctuation value distributions in the wide direction and the narrow direction of the mold with and without EMS is shown in figure 4.

As can be seen in figure 3 and figure 4: whether with or without EMS, level fluctuation around the mold nozzle is apparently higher than elsewhere. The maximum fluctuation value in the wide direction and the narrow direction of the mold is 4.24mm and 4.14mm without EMS. The range of level fluctuation value was slightly reduced when the EMS was applied. The maximum fluctuation value in the wide direction and the narrow direction of the mold is 4.08mm and 3.73mm. Due to the application of electromagnetic stirring, the molten steel in mold moves spirally along the mold axis by the electromagnetic force (figure 2(b)). Then, the impact force of strand flow on the molten steel has deceased and the disturbance of strand flow on the upper surface of the mold has also been weakened.

3.2. The effects of current on fluctuation of liquid level

Figure 5 shows the three-dimensional level fluctuations under various current intensity when the stirring frequency is 2Hz. Figure 6 lists the level fluctuation value distributions in the wide direction and the narrow direction of the mold. It is noted from figure 5 and figure 6 that the fluctuation range of the liquid level in the mold rises with the increase of current intensity and that the maximum site of the level fluctuation occurs near the submerged entrance nozzle (within the scale of 0.5 to 0.1m in the radial direction) and presents as a convex shape. When the current is 450A, 550A or 600A, the largest fluctuated values in the wide direction and the narrow direction of the mold are 3.11mm, 3.29mm or 4.08mm and 3.26mm, 3.27mm or 3.80mm, respectively. The current intensity should not be too big under the condition of electromagnetic stirring. Thus, the fluctuated value of the liquid level must be closely controlled within 4mm when the current is less than 600A. Meanwhile, the powder in the vicinity of the nozzle should be evenly distributed and be supplemented timely in order to protect the surface of the molten steel from being exposed when faced with large liquid fluctuation.

Figure 5. The three-dimensional liquid level fluctuations under 450A (a), 500A(b) and 600A(c) stirring current.
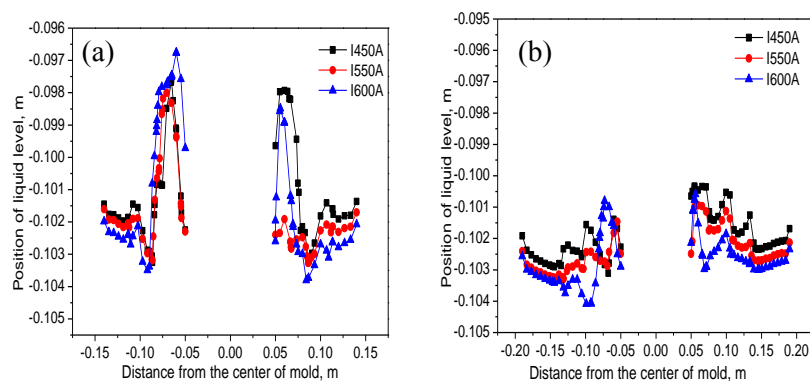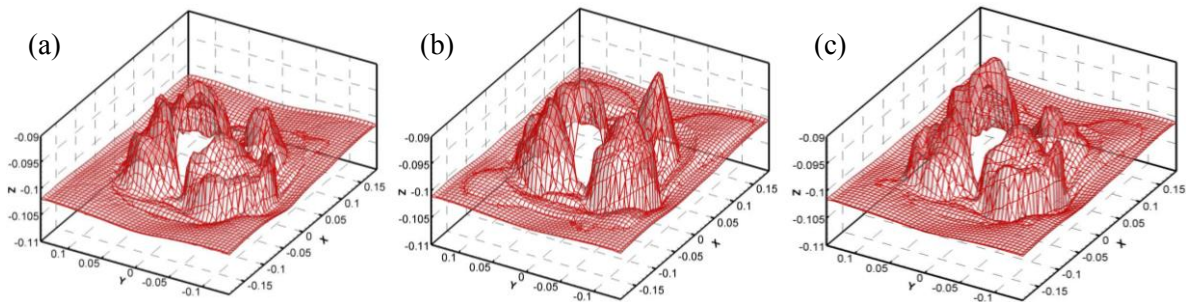

Figure 6. The level fluctuation value distributions in the wide direction (a) and the narrow direction (b) of the mold under different stirring current.

3.3. The influence of frequency on the level fluctuation

Figure 7 shows the three-dimensional level fluctuation in the mold under different stirring frequencies with the current intensity at 600A. The level fluctuation value distributions in the wide direction and the narrow direction of the mold are shown in figure 8.

Figure 7. Three-dimensional diagrams of level fluctuation under 1.5Hz (a), 2.0Hz (b) and 2.5Hz (c) stirring frequency.
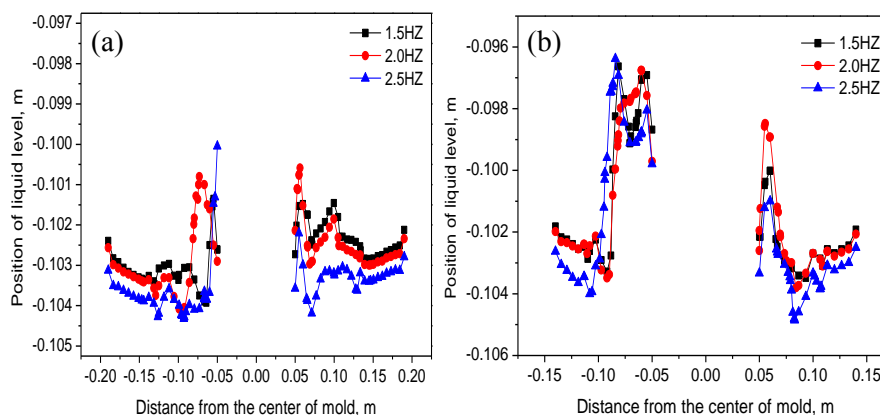
Figure 8. The level fluctuation value distributions in the wide direction (a) and narrow direction (b) of the mold under different stirring frequencies.

As can be seen in figure 7 and figure 8: with the increase of current frequency, the amplitude of liquid level fluctuation in the mold increased accordingly, the waveform gradually steepened, and the maximum fluctuation value all appeared nearby the nozzle (radial distance within 0.5m~1m). When the current frequencies are 1.5Hz, 2.0Hz and 2.5Hz, the maximum level fluctuation in the wide direction and the narrow direction of the mold are 3.93mm, 4.08mm and 4.29mm, and 3.49mm, 3.80mm and 4.86mm, respectively. When EMS is applied, the stirring frequency should not be too high. When the frequency was under 2.0Hz, the liquid fluctuation value was under 4mm.

4. Conclusions

- Compared with the bloom casting mold without electromagnetic stirring, the molten steel in the mold with EMS moves in a circular way under the rotating electromagnetic force, so that the fluctuations of the free liquid level decrease slightly and the maximum level fluctuation value decreases from 4.24mm to 4.04mm.
- The level fluctuation in the mold is enhanced with increasing current intensity and frequency by using electromagnetic stirring. The level fluctuation values in the mold are under 4mm when the current is less than 600A and the frequency is lower than 2Hz.
- With electromagnetic stirring, the maximum site of the liquid level occurs in the vicinity of the submerged entrance nozzle. In the practical continuous casting process, much more

attention should be paid to the thickness of the covering slag to protect the surface of the molten steel from being exposed in air caused by fierce fluctuations.

References

[1]   Liu X D, Yang X D and Zhu M.Y 2007 *Journal of Iron and Steel Research* **14** 6
[2]   Li Y, Ni H.W and Zhang H 2012 *Special Steel* **33** 10
[3]   Zhou L, Tang P and Li Y X 2006 *Iron Steel Vanadium Titanium* **27** 10
[4]   Ren B Z, Zhu M Y and Wang H D 2008 *Acta Metallurgical Sinica* **44** 507
[5]   Liu H P and Wang Z Y 2002 *Research on Iron & Steel* **4** 47
[6]   Wang Y F and Zhang L F 2010 *ISIJ International* **40** 1777
[7]   Wang W W, Zhang J Q and Chen S Q 2007 *Journal of university of science and technology Beijing* **29** 816
[8]   Ren Z P and Jiang M F 2006 *Steelmaking* **22** 16
[9]   Yue Q, Zhou L and Wang J J 2011 *The Chinese Journal of Process Engineering* **11** 187
[10]   Choi S L, Ryu K J and Park H S 2002 *Metals and Material International* **6** 527
[11]   Tan LJ, Shen H.F and Liu B C 2003 *Acta Metallurgical Sinica* **39** 435
[12]   Zhang Q Y and Wang X H 2010 *Journal of Iron and Steel Research* **17** 15