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Effect of Electromagnetic Frequency on the Flow Behavior in Mold during Bloom Casting

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Abstract: Considering solidification, a large eddy simulation (LES) model of two-phase flow was established to simulate the thermal–magnetic flow coupled fields inside a jumbo bloom. The magnetic field was calculated based on Maxwell’s equations, constitutive equations, and Ohm’s law. An enthalpy–porosity technique was used to model the solidification of the steel. The movement of the free surface was described by the volume of fluid (VOF) approach. With the effect of electromagnetic stirring (MEMS), the vortices in the bloom tended to be strip-like; large vortices mostly appeared in the injection zone, while small ones were found near the surface of the bloom. It is newly found that even though the submerged entry nozzle (SEN) is asymmetrical about the bloom, a biased flow can also be found under the effect of MEMS. The reason for this phenomenon is because the magnetic force is asymmetrical and transient. A high frequency will reduce the period of biased flow; however, the frequency should not be too high because it could also intensify meniscus fluctuations and thus entrap slag droplets in the mold. The velocity near the solidification front can also be increased with a higher frequency.

Keywords: round bloom; biased flow; large eddy simulation; enthalpy–porosity method; MEMS



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1. Introduction

Jumbo round blooms are widely used to produce seamless bars, wheels, and tubes. Compared with die casting, continuous casting (CC) is more efficient and thus has been used to lower costs and increase profits for industrial plants. However, many defects such as cavities, segregation, and center porosity may occur in CC, especially as the bloom size increases. As a result, there are rarely reports on jumbo round blooms with a diameter larger than 700 mm. It is urgent to gain a deep understanding of the flow characteristics inside jumbo blooms.

In order to reduce the defects stated above, mold electromagnetic stirring (MEMS) is introduced to control inclusions, reduce segregation, eliminate cavities, and enlarge the equiaxed zone in a continuous casting process. Its essence is that flow patterns can be modified through rotary flow using MEMS to strengthen fluid flow in the mold. However, the magnetic parameters are hard to determine because they can cause meniscus fluctuations and slag entrapment if not properly handled. Due to the hazardous environment, it is hard to perform experiments inside the mold. Currently, water models are widely used to investigate the fluid flow in slabs and billets and have revealed many phenomena. However, MEMS is hardly performed in these models because the electrical conductivity of water is much lower than that of steel. Furthermore, liquid metals with adequate electrical conductivity are often too difficult to handle and very expensive. Therefore, full coupling simulations are essential to gain a better understanding of the whole process.

In recent decades, many studies have been carried out to understand electromagnetically driven flows and the application of a magnetic field with rotary electromagnetic stirring in continuous casting systems. Spitzer et al. [1] established a 2D mathematical model to calculate magnetic force. A simulation was performed using this model. Based on

the differential–integral potential formulation of electromagnetic fields, Natarajan et al. [2] reported that the traveling magnetic field suppresses the inclusion of mold powder in the case of high-speed casting. Dubke et al. [3] used CFD to investigate flow characteristics in the rotary and vertical electromagnetic stirring of blooms and slabs on somewhat idealized continuous casting systems. Ren et al. [4] found that with an increase in the current frequency, the electromagnetic force density at R/2 and R/3 of a $\Phi 600$ mm round bloom first increases and then decreases, reaching a maximum at 10 Hz. Yang et al. [5] investigated the relationship between inclusion entrapment, inclusion size, and meniscus fluctuation under the effect of MEMS. Geng et al. [6] studied the influence of the current density and frequency on the effect of the center equiaxed grain proportion and macroscopic defects of round blooms. Ren et al. [7] developed a 3D model to investigate the swirl flow velocity distribution, jet penetration depth, and temperature distribution in the mold. Liu et al. [8,9] investigated the electromagnetic field and flow pattern using the k - ϵ model. A 3D electromagnetic field, electromagnetic force distribution, electromagnetically driven flow, and meniscus level fluctuation were quantitatively presented. They provided a relatively theoretical insight into how to optimize the stirring parameters to best operate in-mold rotary MEMS by numerical simulation. Moreover, the nozzle type [10], thermal field [11], and electromagnetic torque distribution [12] were investigated to reveal the effect of EMS on the fluid flow in the mold. In a series of works by Fujisaki et al. [13,14], 3D magnetohydrodynamic calculation models were established to evaluate the characteristics of molten metal, with consideration of the fluid flow, heat transfer, solidification, and free surface in linear mold EMS for billet and slab casters.

In those investigations, most of the mathematical simulations were performed using Reynolds-averaged Navier–Stokes (RANS) models. However, limited by RANS's nature, some important details about the transient flow field were inevitably ignored. In recent years [15–19], a more advanced LES model has been adopted to explore the transient asymmetrical flow inside the mold strand. Yuan et al. [16] combined LES with particle image velocimetry (PIV) apparatus in a scaled water model. Many transient phenomena concerning asymmetrical flow patterns were found between the two rolls, and the periodicity of biased flow was identified. Ramos-Banderas et al. [19] studied fluid flow using LES and PIV, finding that the asymmetrical flow changed with time as a consequence of the vertical oscillation of the jet core. Recently, Liu et al. developed different LES models for single-phase (molten steel) flow [20] and two-phase (molten steel and argon gas) flow [21] inside a slab mold. Both simulation results agreed acceptably well with the water model experimental measurements. The flow pattern in the lower recirculation zone is asymmetrical and changes over a certain period; however, the periodical flow in these studies was found in slabs with a two-port submerged entry nozzle (SEN). Until now, there have been few reports about asymmetrical flows injected from a straight nozzle, except for some works by Willers [22] and Li [23]. Based on the experiment of Willers [22], there exists a secondary motion in the upper part of the mold, and this causes a strong deformation of the free surface during and after MEMS. Li [23] built a mathematical model to reveal this phenomenon, and the characteristics of slag–metal interface fluctuations were revealed. In addition, Lin [24] built a water model and found that this biased flow existed in the bloom. However, the reasons for or mechanisms of asymmetrical flows are still not clear at present. This information is important for finding effective methods to control inclusions and decrease segregation to improve the quality of round blooms. Therefore, large eddy simulations coupling melt flow, solidification, and electromagnetic fields are essential to recognize this phenomenon.

The main purpose of this study was to show the periodicity of this biased flow, to find the mechanisms of this phenomenon, and to show the effect of frequency on the periodical flow of casting blooms. This study is helpful for controlling biased flow when developing large-scale steel.

2. Mathematical Model

2.1. Assumptions

In order to simplify the model and calculation, the following assumptions and simplifications are incorporated in the current model:

- (1) The displacement current in Maxwell's equations is ignored because the frequency is low;
- (2) The mushy zone is modeled as a porous medium, in which the flow obeys Darcy's law;
- (3) The curvature of the mold and strand is neglected.

2.2. Electromagnetic Equations

The electromagnetic field formulas [25–27] for mold electromagnetic stirring include constitutive equations, Ohm law's, and Maxwell's equations.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \quad (1)$$

$$\nabla \times \vec{H} = \vec{J} \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

$$\vec{B} = \mu \vec{H} \quad (4)$$

$$\vec{J} = \sigma \left(\vec{E} \right) \quad (5)$$

where σ is the electrical conductivity of the materials, S/m; $\vec{B}$ is the magnetic flux density, T; $\vec{E}$ is the electric field strength, V/m; $\vec{H}$ is the magnetic field strength, A/m; $\vec{J}$ is the current density, A/m²; μ is the magnetic permeability of molten steel, H/m.

2.3. VOF Approach

VOF is used to track the motion of a free surface. In this model, air and steel share the same set of equations; as a result, the filter density ρ and velocity u_i are no longer constants [28]. In the VOF model, all the physical parameters in the interface can be described as the weighting of the volume fraction for each phase. Then, the equations are written as follows:

$$\rho = \alpha_s \rho_s + (1 - \alpha_s) \rho_a \quad (6)$$

$$\bar{u}_i = \alpha_s \bar{u}_{s,i} + (1 - \alpha_s) \bar{u}_{a,i} \quad (7)$$

$$\frac{\partial \alpha_s}{\partial t} + \nabla \cdot (\alpha_s \bar{u}_i) = 0 \quad (8)$$

where t is time, s; α_s is the fraction of molten steel; $\bar{u}_{s,i}$ and $\bar{u}_{a,i}$ are the filter velocity of steel and air, respectively, m/s; ρ_s and ρ_a are steel and air density, respectively, kg/m³.

2.4. LES Model

Filtering the continuity and momentum equations, the continuity equation can be written as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \bar{u}_i) = 0 \quad (9)$$

The LES model and momentum equations can be defined as

$$\frac{\partial (\rho \bar{u}_i)}{\partial t} + \nabla \cdot (\rho \bar{u}_i \bar{u}_j) = -\nabla \bar{P} + (\mu + \mu_t) \nabla^2 \bar{u}_i - \nabla \cdot \tau_{ij} + \vec{F}_{mag} + F_T + S_m \quad (10)$$

where μ is the dynamic viscosity of molten steel; $\bar{P}$ is the filter pressure; τ_{ij} is the sub-grid scale stress; u_s is the casting speed; A_{mush} is a mushy zone parameter; β is the liquid fraction in the solidification and melting zone; F_T is the surface tension force between air and steel; $\vec{F}_{mag}$ is the magnetic force, which can be written as

$$\vec{F}_{mag} = \vec{J} \times \vec{B} \quad (11)$$

where S_m is the source term of the momentum force, the equation of which can be written as [29]

$$S_m = -\frac{(1-\beta)^2}{\beta^3 + 0.001} A_{mush} (\bar{u}_i - u_s) \quad (12)$$

The sub-grid scale stress τ_{ij} is written as

$$\tau_{ij} = \frac{1}{3} \tau_{kk} \delta_{ij} - 2\mu_t \bar{S}_{ij} \quad (13)$$

where τ_{kk} is the isotropic part of the sub-grid scale stress, which can be neglected because the turbulent Mach number of the flow is low; δ_{ij} is the Kronecker delta; $\bar{S}_{ij}$ is the strain rate; μ_t is the turbulent viscosity determined by the Smagorinsky–Lilly model:

$$\mu_t = \rho L_s^2 |\bar{S}| \quad (14)$$

where $\bar{S}$ is a value related to $\bar{S}_{ij}$, and L_s is the mixing length for sub-grid scales.

2.5. Solidification Models

The enthalpy–porosity approach is used to simulate the solidification of steel. It treats the liquid–solid mushy zone as a porous zone. The liquid fraction (0.0–1.0) is used to describe the mushy zone. The liquid fraction β can be defined as

$$\begin{cases} \beta = 1, & \text{if } T > T_{liquidus} \\ \beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}}, & \text{if } T_{solidus} < T < T_{liquidus} \\ \beta = 0, & \text{if } T < T_{solidus} \end{cases} \quad (15)$$

For solidification/melting problems, the energy equation is written as

$$\frac{\partial(\rho H)}{\partial t} + \nabla \cdot (\rho \bar{u}_i H) = \nabla \cdot (k \nabla T) + S_e \quad (16)$$

where H is the enthalpy of the material, and S_e is the source term of energy, which can be written as

$$S_e = \rho L u_s (1 - \beta) - \rho L \frac{\partial \beta}{\partial t} \quad (17)$$

where u_s is the solid velocity due to the pulling of the solidified material out of the domain (also referred to as the pull velocity), and L is the latent heat, J/kg.

2.6. Geometry Model and Boundary Conditions

The MEMS is installed outside the $\Phi 700$ mm-diameter casting strand, as shown in Figure 1. The MEMS system is surrounded by an air box, in which all the magnetic flux lines are closed. Boundary conditions are assigned on this box surface: zero tangential H field. This boundary condition is applied to the external boundaries of the calculated domain, the H field of which is normal to the assigned surface.

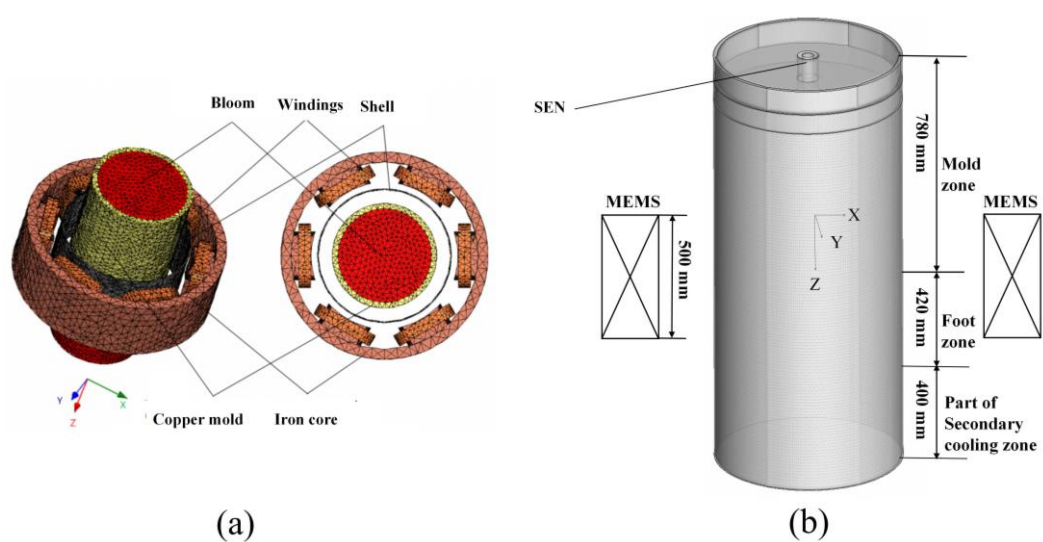


Figure 1. Geometry model and mesh plot in a round bloom strand with MEMS: (a) model used for electromagnetic simulation (surrounding air not shown), and (b) model used for the flow simulation.

The free surface is 168 mm below the mold top, and the straight-through submerge entry nozzle (SEN) is inserted 118 mm below the free surface. The MEMS equipment is composed of one steel core and three pairs of windings with a height of 500 mm. The mid-plane of the stirrer and the mold exit overlap. The coordinate origin is located at the top of the stirrer, and the magnitude of the casting speed is applied along the positive Z coordinate. Figure 1 also shows the calculated domain, which is composed of three zones: the mold cooling zone, foot zone, and part of the secondary cooling zone. The length of each cooling zone is 780 mm, 340 mm, and 400 mm, respectively.

The inlet velocity of the SEN is calculated through mass conservation equations. The outlet of the fluid domain is set as outflow with an initial steel fraction of 1, and the volume of fluid (VOF) model is adopted to track the level fluctuations in the mold. The initial velocity for steel is patched as the casting speed because the fluid will be pulled out at the same time as long as it has solidified.

The jumbo bloom is cooled by water inside the mold, the heat flux of which is calculated using a uniform heat flux equation of 473040 W/m^2 . The steel flows out of the SEN at a temperature of 1803 K, with an initial zone temperature of the melt at 1790 K. The heat transfer coefficients for the foot zone and the following part of the secondary cooling zone are calculated using the equation presented in [23]. The geometrical, operating, and physical parameters used in this paper are summarized in Table 1.

2.7. Numerical Details

The magnetic Reynolds number in CC is so small that the movement of the steel does not affect the electromagnetic field. As a result, the numerical simulation can be divided into two sections: (1) the electromagnetic simulation is performed using the finite element method (FEM); (2) the flow field is coupled with the electromagnetic field. First, the magnetic field is calculated by solving magnetic equations using the equations stated above. Then, the temperature field and velocity field for the round bloom, coupled with MEMS, are calculated by solving mass conservation equations, N–S equations, and energy equations.

Table 1. Simulation parameters in this study.

Parameters	Values	Parameters	Values
Diameter of round bloom, mm	700	Melting heat of steel, J/kg	714,000
Thickness of mold, mm	40	Dynamic viscosity of steel, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$	0.00471
Diameter of MEMS, mm	1550	Dynamic viscosity of slag, $\text{kg}\cdot\text{m}^{-1}\cdot\text{s}^{-1}$	0.4
Super heat, K	16	Density of molten steel, kg/m^3	7100
Current, A	310	Density of slag, kg/m^3	2000
Frequency, Hz	0.5, 1.5, 2.5	Specific heat of steel, $\text{J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$	710
Number of turns	80	Thermal conduction of molten steel, $\text{W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$	43
Casting speed, m/min	0.21	Iron core relative permeability	1000
Liquidus temperature of steel, K	1787	Electrical conductivity of molten steel, S/m	714,000
Solidus temperature of steel, K	1760	Electrical conductivity of mold, S/m	17,800,000

In order to capture enough large-scale eddy structure characteristics to analyze the dynamic state of the molten steel inside the mold, the calculation domain is divided to obtain 1.23×10^5 finite volumes. The boundary layer is refined to calculate the heat transfer between water cooling and the molten steel. The time-dependent filtered Navier–Stokes equations are solved using the SIMPLE pressure–velocity coupling terms. Bounded central differencing is used for the momentum discretization terms. Furthermore, in order to ensure the convergence of the calculation, the implicit algorithm of VOF is adopted. The time step size is 1×10^{-3} s, and the total calculation time is 100 s.

3. Model Validation

3.1. Magnetic Flux Density

In order to show the accuracy of the calculated magnetic field, a simulation was conducted using Yu and Zhu's [30] geometry model, and the result is shown in Figure 2. In their experiment, the magnetic flux density was tested along the strand axis at the condition of 300 A/2.5 Hz (without liquid steel in the mold). It can clearly be seen that the simulation result is distributed evenly along both sides of the experiment result, and there is not much difference between the two sets of data. This indicates that the magnetic model in our work is reliable.

3.2. Surface Temperature Distribution

In order to check the accuracy of our mathematical model for heat and mass transfer, the temperature data were acquired from a steel cooperation and compared with the simulated result, shown in Figure 3. It can be seen from Figure 3 that the steel temperature decreases sharply during mold cooling. After the steel flows out of the mold and goes to the foot zone, the temperature recovers to 1315 K, which is 100 K higher than the temperature at the mold exit. This is because the cooling rate in the foot zone is lowered. The predicted temperature agrees well with the practical measurement, so the solidification growth is confirmed to be reliable.

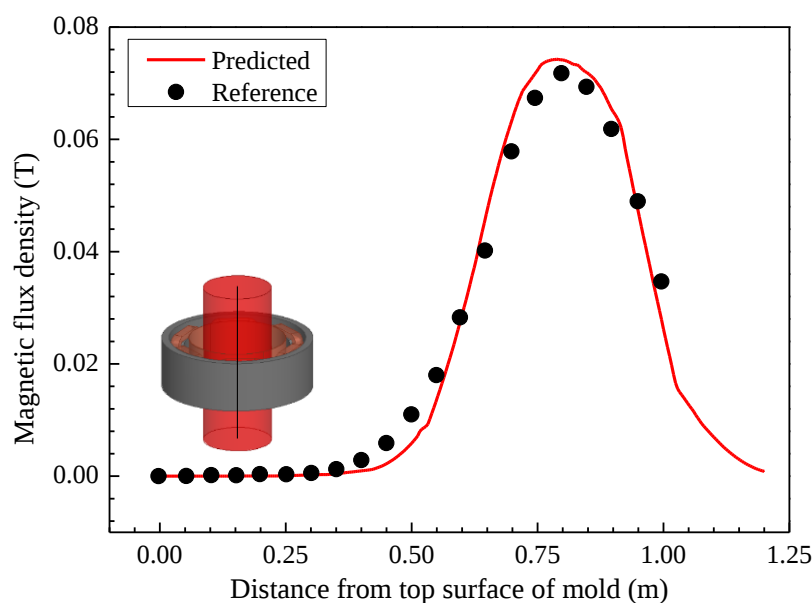


Figure 2. Comparison of the magnetic flux density along the axis of the stirrer using the data in reference [30]. Reprinted with permission from [30]. Copyright 2021 Acta Metallurgica Sinica.

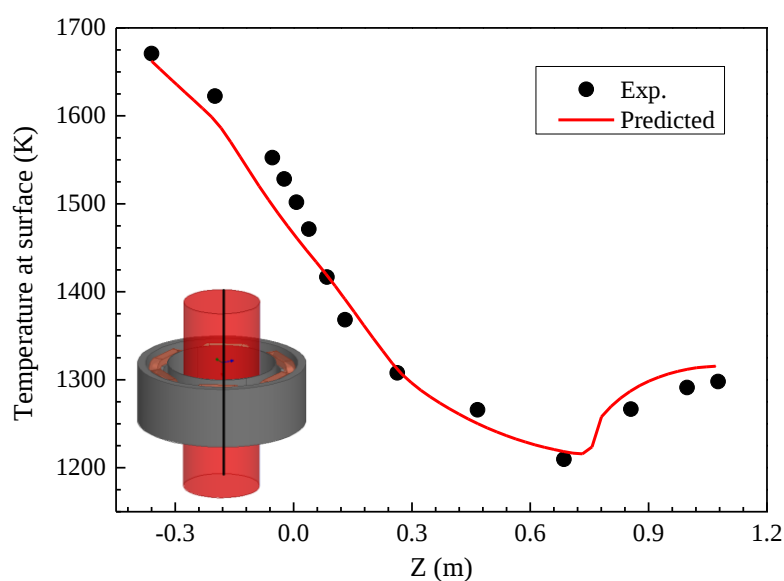


Figure 3. Comparison of the predicted and measured temperature along the surface line of $Y = 350$ mm.

4. Results and Discussions

4.1. Effect of Magnetic Parameters

Figure 4 shows the magnetic flux density distribution at the mid-plane of the stirrer. The results reveal that the vectors of the magnetic flux density are almost parallel, rotating periodically in T_B (T_B is the reciprocal of the current frequency). The maximum value is located at the surface of the strand and decreases with the distance from the surface to the center of the bloom. The magnetic flux density occasionally varies, which has a great effect on the flow field during bloom casting.

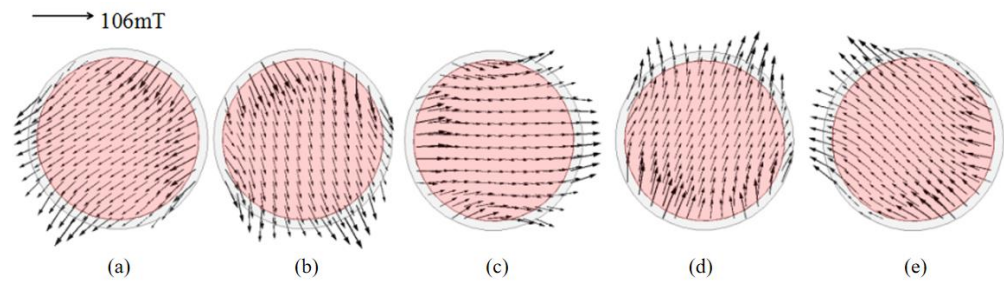


Figure 4. Magnetic flux density vectors at mid-plane of the stirrer: (a) 0, (b) $1/5 T_B$, (c) $2/5 T_B$, (d) $3/5 T_B$, (e) $4/5 T_B$.

The transient distribution of the magnetic force for a typical position is shown in Figure 5. The monitored point is located on the center plane of the stirrer, on the half radius of the round bloom. The operating condition is 310 A/2.5 Hz. It can easily be seen in Figure 5 that the magnetic force presents a sinusoidal form in stirring and occasionally changes at a permanent period of $T_B/2$. This is also in accordance with theory research, indicating that the accuracy of our mathematical model is reliable.

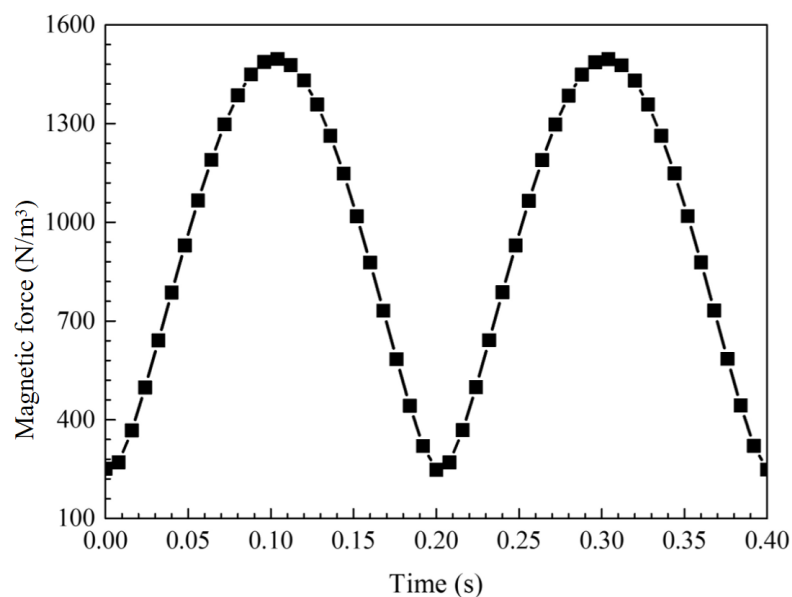


Figure 5. The magnetic force monitored on the center plane of the stirrer, on the half radius of the round bloom.

Figure 6 shows that the transient distribution of the magnetic force is at the center plane of the stirrer. The solidified shell is shown around it. The operating condition is 310 A/2.5 Hz. It can be seen in Figure 6 that the magnetic force distribution is obviously transient and asymmetrical at transverse sections and is rotated clockwise in half T_B , presenting a complex but regular distribution in this period. Seen from the top, the maximum magnetic force is located at the boundary of the bloom and decays with the distance from the boundary to the center of the mold. This asymmetrical distribution of the magnetic force may have a great influence on the flow field in the mold. Additionally, it can also be seen in Figure 6 that the solidified shell sufficiently resists the magnetic force in the liquid steel; thus, the solidified shell should not be ignored.

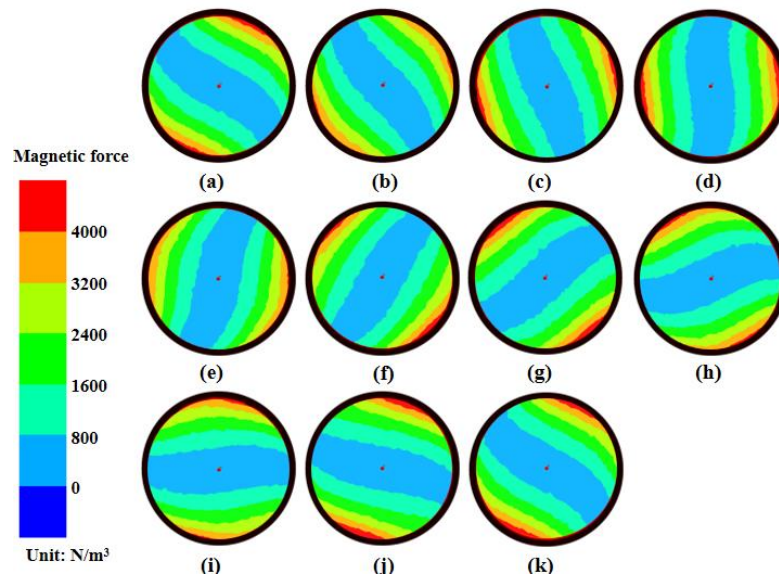


Figure 6. The transient distribution of the magnetic force with a solidified shell at different times of: (a) 0, (b) $1/20 T_B$, (c) $2/20 T_B$, (d) $3/20 T_B$, (e) $4/20 T_B$, (f) $5/20 T_B$, (g) $6/20 T_B$, (h) $7/20 T_B$, (i) $8/20 T_B$, (j) $9/20 T_B$, (k) $10/20 T_B$.

Figure 7 shows the distribution of the magnetic force with different frequencies. The data were acquired from the transverse direction of the Y-axis, on the center plane of the stirrer. It can be seen in Figure 7 that the force decays from the boundary to the center of the bloom and increases with the stirring frequency. Thus, the frequency has a great effect on the magnetic flow field during bloom casting.

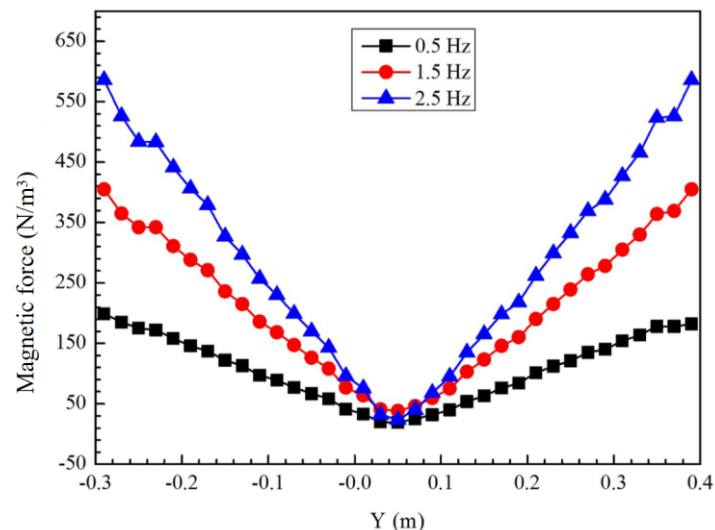


Figure 7. The magnetic force density distribution at different frequencies.

4.2. Flow Characteristics

Figure 8 illustrates the transient vectors and solidification shell growth inside the mold. It can be seen in Figure 8 that there is an obvious biased flow after injection from the SEN. Seen from the top, the steel is rotated under the effect of MEMS. The velocity near the center plane reaches the maximum value, while it decays with the distance from the center plane of the stirrer. It is also interesting to find that the injection flow biases to the

right under the effect of MEMS. The reason for this phenomenon can be found in Figure 6, which shows that the magnetic force is inharmonious at each time point.

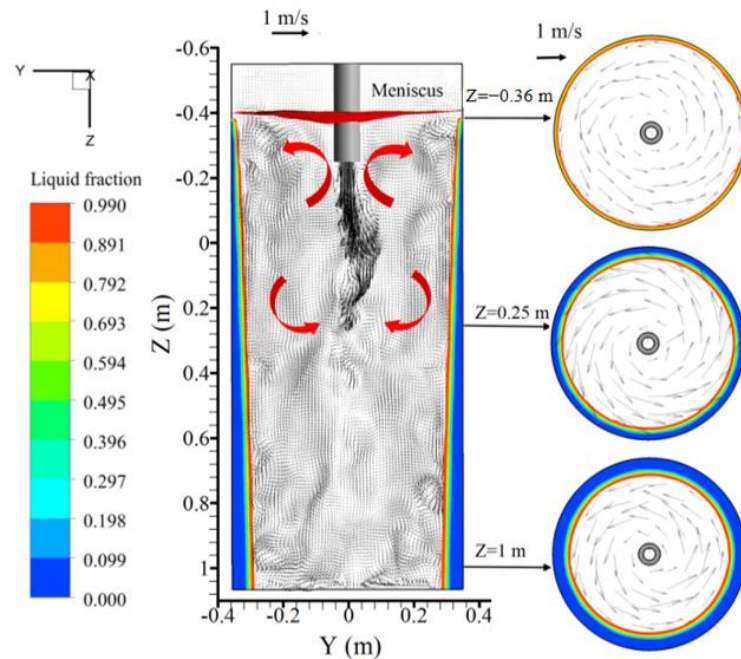


Figure 8. Transient vectors and solidification shell growth at conditions of 310 A/2.5 Hz.

Figure 9 presents the transient velocity at different frequencies. It can be seen that the injection depth decreases with the frequency, while the velocity near the solidified shell increases. This indicates that a high frequency would significantly reduce the injection depth of the molten steel. The reason for this phenomenon is that a high frequency causes a stronger magnetic force in the steel. Moreover, it can also be found that the injection flow is biased under the effect of MEMS. Therefore, in order to study the behavior of the biased flow, three points were selected near the end of the injection depth.

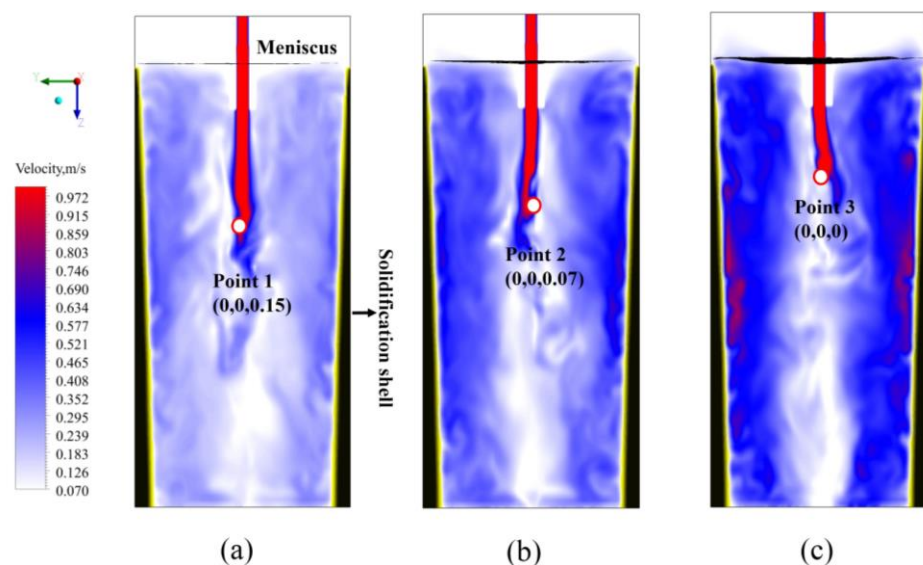


Figure 9. Transient contours of velocity at conditions of (a) 310 A/0.5 Hz, (b) 310 A/1.5 Hz, and (c) 310 A/2.5 Hz.

Figure 10 illustrates typical instantaneous transient vortex distributions with different frequencies from the front and top views obtained from the LES model. Seen from the front view, large vortices are mostly observed in the injection zone, while small strip-like vortices are clearly found near the surface of the bloom. The small vortices are induced under the magnetic force and help release heat into water cooling, which may promote homogenization of the temperature distribution in the mold and contribute to the columnar-to-equiaxed transition (CET) of the jumbo bloom. High frequencies produce more large-scale vortices than low frequencies, and these vortices help to release the heat injected from the SEN.

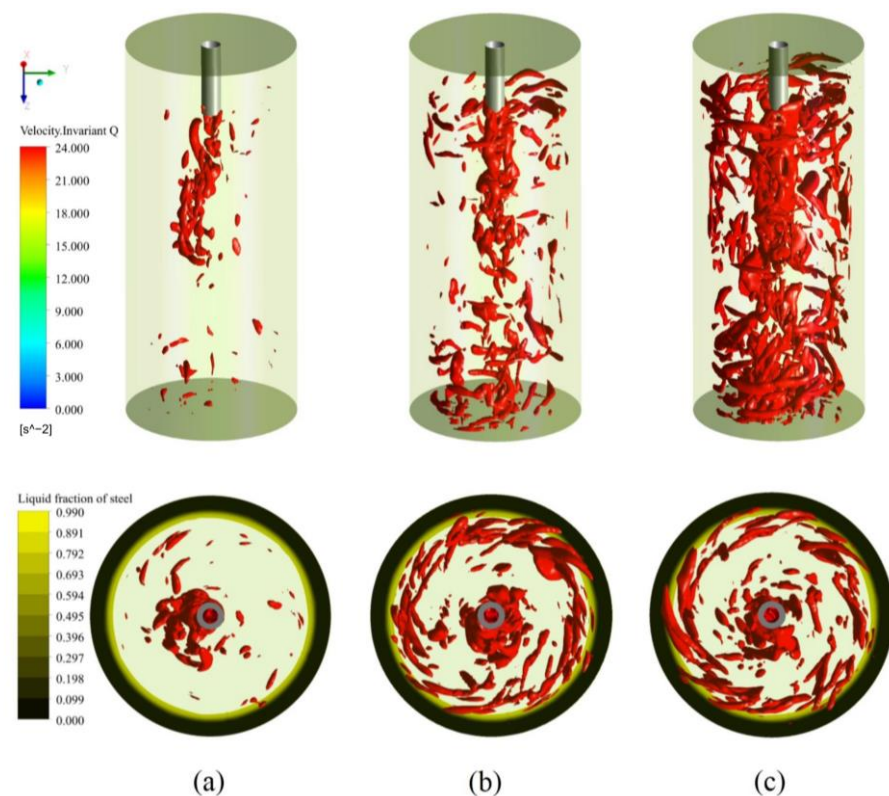


Figure 10. Velocity vectors and solidification shell growth at conditions of (a) 0.5 Hz, (b) 1.5 Hz, and (c) 2.5 Hz.

4.3. Evolution of Asymmetrical Flow Pattern

Figure 11 shows the tangential velocity at different frequencies, the position of which is 1.13 m below the mold top. The negative value indicates that the flow is along the positive X-axis. It can clearly be seen that the tangential velocity increases with the frequency, reaching a maximum near the solidification shell, and decreases from the boundary to the center. A high frequency may induce high velocity near the solidification front; however, it may also help remove inclusions near the solidified shell. Thus, the frequency should not be too high because it may intensify level fluctuations and induce slag entrapment in the mold.

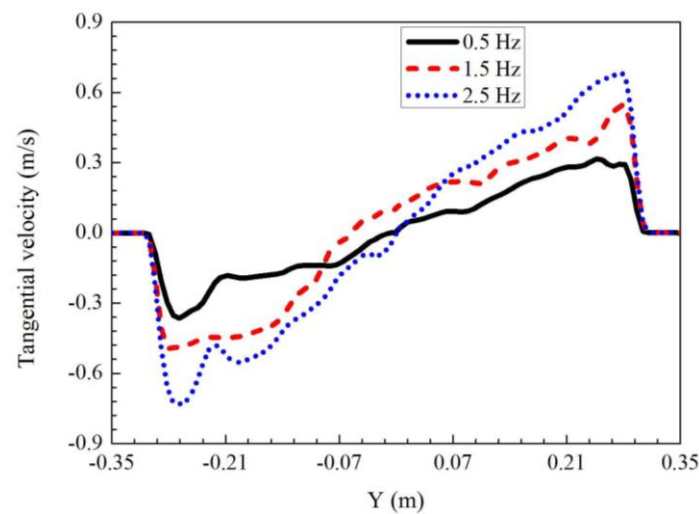


Figure 11. Tangential velocity at solidification front with different frequencies.

4.4. Periodicity of Asymmetrical Flow Pattern

Many researchers have reported that the flow pattern inside the slab mold is not stationary but changes frequently. However, the SEN used in the slab usually has two ports with a certain opening angle rather than a straight nozzle. Reports of biased flow for a straight nozzle are hardly seen at present. Different from previous works, the periodical asymmetrical flow pattern inside the round bloom was identified and characterized in the present work. Figure 12a–d present the transient flow pattern inside the mold at different times. Long-term flow asymmetry is observed, and the flow pattern constantly changes. This result indicates that the mold turbulent field is transient and random and reveals the periodical flow in the bloom strand. At 51 s (Figure 12a), the left jet begins to turn right, and 6 s later, in Figure 12b, the jet reaches the right part and begins to turn left. The same loop continues through a range of periods, indicating that biased flow can also be found in a straight nozzle. The reason for this phenomenon is the asymmetry distribution of the magnetic force during the casting process, which can be found in Figure 6.

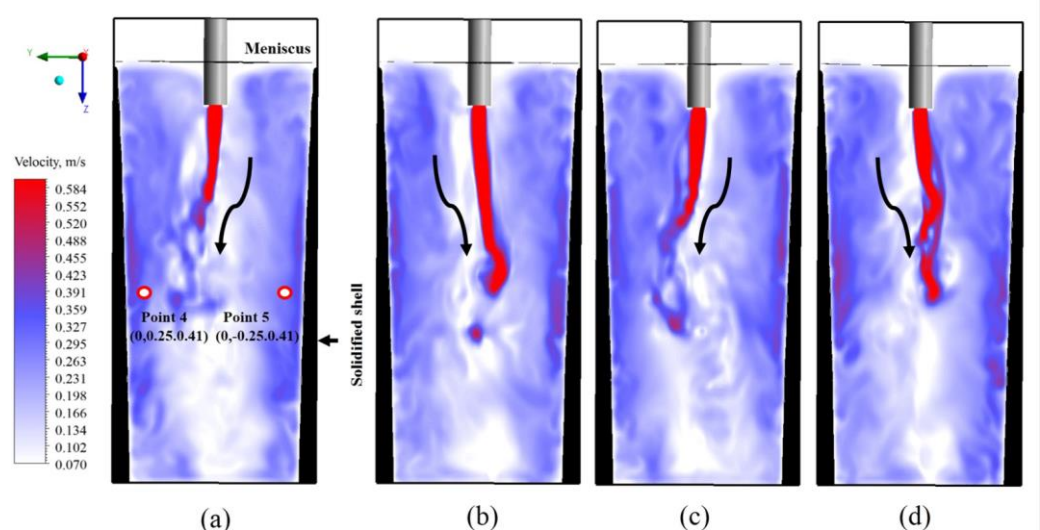


Figure 12. Evolution of asymmetrical flow pattern inside the mold, including two processes: left to right (a to b), right to left (b to c), and left to right (c to d).

Figure 13a–b show the model predictions of the steel velocity at two symmetrical points (Point 4 and Point 5, see Figure 12a). The velocities are always high and variable.

The plot clearly indicates that the velocity of the two symmetrical points occasionally fluctuates, and the variation at each time point is different. There are often peaks and troughs at certain points, and the mean velocities of the two points are not equal, indicating that the jets are not symmetrical between the sides of the SEN.

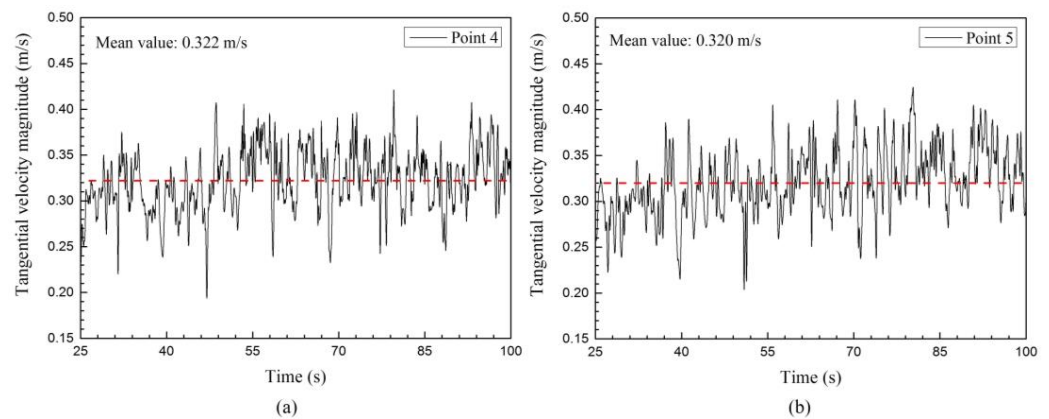


Figure 13. Time history of two symmetrical points, (a) Point 4 and (b) Point 5, at conditions of 310 A/0.5 Hz.

Figure 14 shows the model predictions for the transient horizontal velocity (v_y) near the end of the injection depth. Three frequencies were considered: 0.5Hz, 1.5Hz, 2.5Hz. The positive and negative values of the horizontal velocity for a long period of time represent the recirculation flow turning to the left side and to the right side of the bloom strand, respectively. The plot clearly indicates that the direction of asymmetric flow changes with time, corresponding to the results in Figure 12. The mean periods for biased flow at the three frequencies are 6.25 s, 5.35 s, and 4.68 s, respectively. This indicates that a high frequency is helpful for reducing the period of biased flow.

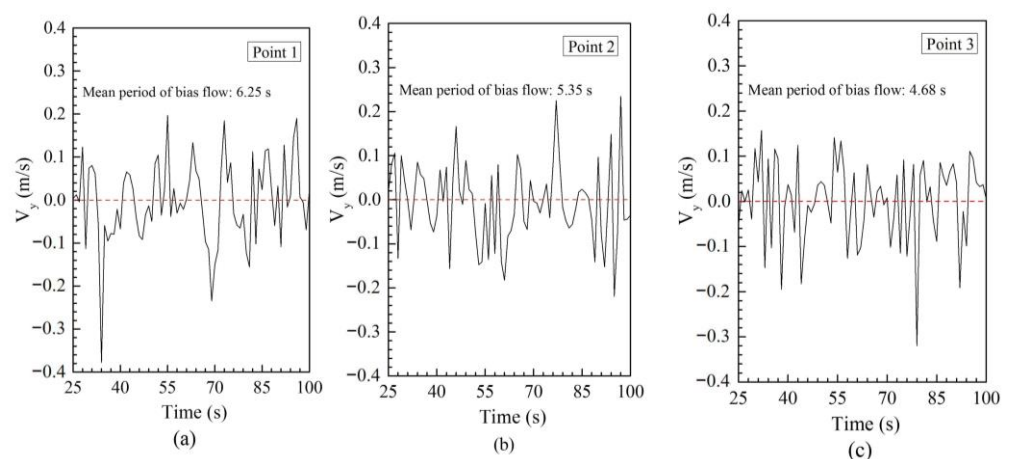


Figure 14. Time history of velocities at monitor points at conditions of (a) 310 A/0.5 Hz, (b) 310 A/1.5 Hz, and (c) 310 A/2.5 Hz.

5. Conclusions

In this study, a new type of biased flow was identified and established through an LES–MEMS coupled model. The conclusions are as follows:

(1) Considering solidification, a large eddy simulation (LES) model of two-phase flow was established to simulate the thermal–magnetic flow coupled fields inside a jumbo bloom. The simulated results were compared with reference and practical measurements, and good agreements were obtained.

(2) The magnetic force imposed on the molten steel changed at a certain period of $T_B/2$ and increased with the frequency. The frequency had a great effect on the distribution of vortices. Large vortices were mostly observed in the injection zone, and many small strip-like vortices were found near the surface. The high frequency produced more large-scale vortices than the low frequency, which is beneficial for releasing heat injected from the SEN.

(3) The periodical behavior of the asymmetrical flow inside the liquid pool was firstly captured using the LES model. The flow was observed to be an instantaneous tangential flow caused by the straight nozzle. The reason for this phenomenon is the asymmetry distribution of the magnetic force.

(4) The biased flow was identified and characterized. Our results show that the steel injected from the SEN varied in a range of periods, and the high frequency reduced the period.

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