Numerical Analysis of the Influences of Operational Parameters on the Fluid Flow in Mold with Hybrid Magnetic Fields

Zhong-Dong QIAN, Yu-Lin WU, Ben-Wen Li¹ and Ji-Cheng HE¹

Department of Thermal Engineering, Tsinghua University, Beijing 100084, P.R. China. E-mail: zhongdongqian@yahoo.com.cn
¹Department of Thermal Engineering, Northeastern University, Shenyang, Liaoning 110004, P.R. China.

(Received on June 6, 2002; accepted in final form on August 5, 2002)

A package of computer programs, which can be used to calculate magnetic fields, induced current, meniscus shape, and fluid flow was developed and applied to the numerical study of effect of hybrid magnetic fields mold. In investigation about the influence of important operating parameters on the effect of hybrid magnetic fields mold, three standards like the followings were used: the flow pattern, the maximum velocity beneath the meniscus, and the dynamic pressure on the contact point. It was found that the hybrid magnetic fields mold has the effects of both EMBR (Electromagnetic Brake) and soft contact EMC (Electromagnetic continuous casting) at the same time. On the other hand, the hybrid magnetic fields mold can overcome some shortcomings of EMBR and soft contact EMC with proper magnitudes of static magnetic flux density and suitable relative position of the two magnetic fields.

KEY WORDS: hybrid magnetic fields mold; numerical simulation; continuous casting.

1. Introduction

EMBR is a technology used to control the molten steel flow in a mold of continuous casting process by adding a transverse static magnetic field. The main advantages of EMBR are the following: reduction of inner or subsurface inclusions, elimination of mold powder entrapment, reduction of static and dynamic waves at the meniscus, increase of meniscus temperature, elimination of remelting at narrow side, etc.¹,²) Soft contact EMC is a technology used to control the initial solidification by adding a high frequency magnetic field. The advantage of soft contact EMC are the following: reduction of the static pressure of metal pool, uniform heating of the upper part of pool, increase of the width of the flux channel gap, decrease of the depth of oscillation mark, etc.³,⁴) However, neither EMBR nor soft contact EMC can improve the surface quality and the inner quality of product at the same time.

The hybrid magnetic fields mold was introduced to improve the surface quality and inner quality of product at the same time. The new mold overcomes some shortcomings of EMBR and soft contact EMC too. Much improvement has been accomplished in Ref. 5 and Ref. 6, nevertheless the influence of operational parameters like static magnetic flux density and relative position of the two magnetic fields on the fluid flow in the new mold has not been published.

In this study, the influences of static magnetic flux density and relative position of two magnetic fields on the velocity beneath the meniscus and the contact pressure was analyzed. Additionally, the causes for the influences have been also discussed.

2. Numerical Method

The structure of hybrid magnetic fields mold is shown in Fig. 1 schematically. There exist four kinds of electromagnetic forces in the metal pool, which can be expressed as

\[ \vec{F}_1 = \vec{j}_a \times \vec{B}_b \]  
\[ \vec{F}_2 = \vec{j}_b \times \vec{B}_a \]  
\[ \vec{F}_3 = \vec{j}_a \times \vec{B}_a \]  
\[ \vec{F}_4 = \vec{j}_b \times \vec{B}_b \]  

However, the time-average values of \( \vec{F}_1 \) and \( \vec{F}_2 \) are zero and can be neglected.⁶) The detail description of electromagnetic forces in the metal pool can be found in Ref. 6). For the numerical computation, the whole process is composed of four unit ones: time varying magnetic field computation,
static magnetic field computation, meniscus shape computation and flow field computation.

### 2.1. Computation of Time Varying Magnetic Field

The electric field intensity \( \vec{E} \), and magnetic field intensity \( \vec{H} \) in the electromagnetic system can be described by Maxwell’s equations. The modified FDTD (finite difference time domain) method\(^3\) is adopted here. For the MKS system of units, Maxwell’s time-dependent curl equations read\(^\text{10}\)

\[
\nabla \times \vec{E}_a = -\mu \frac{\partial \vec{H}_a}{\partial t} \quad \text{(5)}
\]

\[
\nabla \times \vec{H}_a = \varepsilon \frac{\partial \vec{E}_a}{\partial t} + \sigma \vec{E}_a \quad \text{(6)}
\]

Details of discretization of Eqs. (5) and (6), and verification of the new method can be found in Ref. 7). The time varying electromagnetic force \( \vec{F}_a \) can be expressed as

\[
\vec{F}_a = \vec{J}_a \times \vec{B}_a \quad \text{(7)}
\]

In the computation of time varying magnetic field, the effect of shapes of the lower coil and the core for static magnetic field was considered.

### 2.2. Determination of the Meniscus Shape

The shape of meniscus is determined following the steps of

1. Time varying magnetic field is computed for the initial shape of the slab using 3-D FDTD code.
2. Magnetic pressure \( P_m \), hydrostatic pressure \( P_b \), and pressure due to surface tension \( P_s \) on the surface of melt are computed according to Ref. 2)

\[
P_m = \frac{\mu H_z^2}{2} \quad \text{(8)}
\]

\[
P_b = \rho g z \quad \text{(9)}
\]

\[
P_s = \Gamma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad \text{(10)}
\]

3. The sum of the above three terms of pressure on surface was obtained at each node on meniscus using the following equation\(^3\)

\[
p_m + p_b + p_s = \text{Const.} \quad \text{(11)}
\]

After comparing the sum at each node, the displacement of the each node is determined and the new shape of meniscus is reconstructed accordingly.

4. The shape of meniscus will be regarded no changes only if the convergence criterion is satisfied. Then the electromagnetic force will be computed finally.

### 2.3. Computation of Static Magnetic Field

The Maxwell equation for static magnetic field reads

\[
\nabla \times \vec{H} = \vec{J}_a \quad \text{(12)}
\]

The vector potential \( \vec{A} \) is introduced to simplify Eq. (12). \( \vec{A} \) can be defined as

\[
\vec{B}_a = \nabla \times \vec{A} \quad \text{(13)}
\]

then the Poisson equation for potential \( \vec{A} \) reads

\[
\nabla^2 \vec{A} = -\mu \vec{J}_a \quad \text{(14)}
\]

According to the Ohm’s law, the induced electric current density in the moving liquid metal can be expressed as\(^1\)

\[
\vec{J}_b = \sigma (-\nabla \varphi + \vec{u} \times \vec{B}_b) \quad \text{(15)}
\]

Then the electromagnetic force for EMBR \( \vec{F}_b \) is obtained from

\[
\vec{F}_b = \vec{J}_b \times \vec{B}_b \quad \text{(16)}
\]

### 2.4. Computation of Velocity Field

The governing equations of continuity and momentum for a steady incompressible fluid are

\[
\nabla \cdot (\rho \vec{u}) = 0 \quad \text{(17)}
\]

\[
\nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{u}) + \nabla \cdot \vec{F}_m + \rho \vec{g} \quad \text{(18)}
\]

where \( \vec{F}_m = \vec{F}_s + \vec{F}_b \).

The standard \( k-\varepsilon \) turbulent model is used to simulate the turbulence of fluid.

### 3. Verification of Simulation of Static Magnetic Field and Meniscus Shape

The structure of the experimental device for measurement of static magnetic field is shown in Fig. 2, and the corresponding dimensional values are listed in Table 1. All the points for measurement were located on the \( x \)-axis of Fig. 2 and the origin was set to the center of the surface of the core. Figure 3 shows the comparison between computational and experimental results. The agreement between the computational and the experimental data can be seen to be excellent.

The physical properties of the alloy and the operating parameter used for verification of the computed meniscus shape are shown in Table 2. Copper plates with 0.3 mm thickness were submerged vertically to the surface of the melt to obtain the shape of meniscus. After a moment of submerging, the metal adhered to the submerged area of the plate and the shape of the meniscus was obtained. From
Fig. 3. Comparison of experimental and computational static magnetic flux density.

Table 2. Physical properties of metal used for verification of meniscus calculation.

| Alloy       | Density (kg/m³) | Melting point (°C) | Electric conductivity (S/m) |
|------------|-----------------|--------------------|-----------------------------|
| Pb-Sn-Bi   | 9500            | 94                 | $1.11 \times 10^5$         |

Fig. 4. Comparison of experimental and computational meniscus shape.

From Figs. 6 and 7, it can be seen that the maximum velocity beneath the meniscus was increased compared with that of conventional slab caster. The dynamic pressure on the contact point was thought to have effect on the surface quality of cast steel. The dynamic pressure on the contact point was added to the standards. Three standards used for analysis of effect of soft contact EMC, EMBR and hybrid magnetic fields mold were classified as followings.

Standard 1: the flow pattern.
Standard 2: the maximum velocity beneath the meniscus.
Standard 3: the dynamic pressure on the contact point.

4. Results and Discussion

Operating parameters considered here are the static magnetic flux density and the relative position of the two magnetic fields (Table 3). Considering the symmetry of the system, only one quarter of the space was discretized using $40 \times 20 \times 100$ rectangular grid system. The electromagnetic field calculation and the meniscus shape calculation were mutually coupled according to Ref. 3).

4.1. Fluid Flow Characteristics in the Mold of Slab Caster with Different Magnetic Fields

Figure 5(a) shows typical fluid flow in the mold without magnetic field. All operating parameters are fixed except that the applied AC current and DC current are set zero value. There can be seen a clear impinging point at the narrow wall side and two strong re-circulating flows. The upward re-circulating flow under the meniscus with high velocity has been known as main cause of mold powder entrapment. One of important roles of the hybrid magnetic fields is to decelerate the velocity of the eddy flow and stabilize the meniscus. Therefore the maximum velocity of flow beneath the meniscus was selected as a standard. The strong downward re-circulating flow could carry nonmetallic inclusions and gas bubbles deeply into strand, thus prevent the floating of such impurities. Another role of hybrid magnetic fields is to suppress the downward re-circulating flow. Therefore, the flow pattern was selected as another standard. The dynamic pressure on the contact point was thought to have effect on the surface quality of cast steel. The dynamic pressure on the contact point was added to the standards. Three standards used for analysis of effect of soft contact EMC, EMBR and hybrid magnetic fields mold were classified as followings.

Standard 1: the flow pattern.
Standard 2: the maximum velocity beneath the meniscus.
Standard 3: the dynamic pressure on the contact point.

Figure 5(b) shows fluid flow in the soft contact EMC mold when 2 000 A of AC electric current is applied. The flow pattern is closely similar to that in conventional slab caster: There can be seen a clear impinging point at the narrow wall and two strong re-circulating flows. But the strength of flow under the meniscus increased compared with that of conventional slab caster, which has detrimental effect on mold powder entrapment. And the width of the flux channel gap increased, which has profitable effect on heat transfer and initial solidification.

Figure 5(c) shows fluid flow in the EMBR mold when 200 A of DC electric current is applied. The impinging point at the narrow wall was eliminated and the two re-circulating flows were suppressed. The strength of flow under the meniscus decreased compared with that of conventional slab caster.

Figure 5(d) shows fluid flow in the hybrid magnetic fields mold when 2 000 A of AC electric current is applied to the upper coil and 200 A of DC electric current to the lower. The impinging point at the narrow wall was eliminated and the two main re-circulating flows were suppressed. The shape of meniscus is closely similar to that of soft contact EMC. A conclusion may be drawn from the flow pattern of Fig. 5(d) that the hybrid magnetic EMC has the effect of both EMBR and soft contact EMC. But it should be noticed that another strong eddy flow appeared at the meniscus portion. The strong eddy flow was induced by time varying electromagnetic force. If the upward re-circulating flow was suppressed, the eddy flow will appear.

From Figs. 6 and 7, it can be seen that the maximum ve-
locity beneath the meniscus and the dynamic pressure on the contact point in hybrid magnetic fields mold are less than those in soft contact EMC mold. So the conclusion may be reached that the hybrid magnetic EMC has the advantage over soft contact EMC mold in controlling the initial solidification and flux powder entrapment. When the magnitude of static magnetic field increased to a large value (more than 0.26 Tesla), the velocity beneath the meniscus kept a more suitable magnitude than that in EMBR mold, which has profitable effect on preventing the meniscus from solidifying.

4.2. Influence of Static Magnetic Flux Density on Fluid Flow

Figure 8 shows the flow patterns in hybrid magnetic EMC mold with different magnitudes of static magnetic flux density. Figures 9 and 10 are obtained according to standard 2 and standard 3 separately. From Fig. 8, it can be noticed that with the increase of static magnetic flux density the eddy flow induced by electromagnetic force appeared gradually. The data in Figs. 9 and 10 imply that the static magnetic flux density doesn’t have linear influence on the maximum velocity and the dynamic pressure on the contact point. “Eddy flow-suppression model” is introduced to summarize the previous discussion (Fig. 11). This figure indicates that the static magnetic field is too far from the meniscus to set direct influence on it, and the flow beneath the meniscus can only be controlled by the direction and strength of the upward re-circulating flow and the upward flow. When the upward re-circulating flow or the upward flow has the same direction as the eddy flow at their meet point, the maximum velocity beneath the meniscus and the dynamic pressure on the contact point increased. The opposite direction will cause opposite results. But the perfect
value (0.08 T) of static magnetic flux density for stabilizing
the meniscus and that (0.13 T) for improving the surface
quality were not adopted, because the magnitude of the stat-
ic magnetic fields is not sufficient for suppressing the jet
flow and the downward re-circulating flow. $B_s=0.26\,T$
was thought perfect for suppressing the jet flow and the down-

Fig. 8. Flow fields in the hybrid magnetic fields mold with different magnitudes of static magnetic flux density.
(a) $B_s=0.03\,T$; (b) $B_s=0.08\,T$; (c) $B_s=0.13\,T$; (d) $B_s=0.26\,T$.

Fig. 9. Relationship between the maximum velocity beneath the
meniscus and static magnetic flux density.

Fig. 10. Relationship between the dynamic pressure on contact
point and static magnetic flux density.

Fig. 11. Eddy flow suppression model for influence of static magnetic field.
(a) $B_s=0$; (b) $B_s=0.13\,T$; (c) $B_s=0.26\,T$. 
ward re-circulating flow in the viewpoint of removing of inclusions and distribution of the remained ones in Ref. 12). Therefore $B_s=0.26$ T was adopted in the following discussion.

4.3. Influence of Relative Position of Magnetic Fields on Fluid Flow

**Figure 12** shows three different positions of the static magnetic field. **Figure 13** shows the flow patterns in hybrid magnetic fields mold corresponding to these three positions. **Figures 14 and 15** show the results from standard 2 and standard 3. From Figs. 14 and 15, it can be seen that the maximum velocity beneath the meniscus does not have the same trend as the dynamic pressure on the contact point. The “Eddy flow-suppression model” can also explain the results (Fig 16). The figure explains that the contact point is a little lower than the meniscus, so the flow at the contact point increased while the flow beneath the meniscus was suppressed when static magnetic field is located on c–c. The most efficient position of the static magnetic field for stabilizing the meniscus is a–a.
5. Conclusion

A mathematical model that could be used to compute hybrid magnetic fields, deformation of meniscus, and fluid flow in hybrid magnetic fields mold was developed. A series of numerical study about the characteristics of three dimensional flow fields in hybrid magnetic fields mold was carried out and the following conclusions were obtained.

(1) Hybrid magnetic fields mold has the effects of both EMBR and soft contact EMC at the same time. With reasonable choices of static magnetic flux density and suitable position, the meniscus in hybrid magnetic field mold can be more stable than that in soft contact EMC, which is beneficial to prevent flux powder entrapment. When a large magnitude of static magnetic flux density (more than 0.26 T) is needed to suppress the jet flow and the two re-circulating flows, the velocity beneath the meniscus keeps a more suitable magnitude than that in EMBR mold, which is beneficial to prevent the solidification of the meniscus.

(2) The static magnetic field is too far from the meniscus to control the meniscus directly. “Eddy flow-suppression model” was introduced to explain the influence of the two operating parameters: the static magnetic flux density and the relative positions of the two magnetic fields.

(3) If other operating parameters are fixed at the values shown in Table 3, the most suitable magnitude of static magnetic flux density is 0.08 T for stabilizing the meniscus and 0.13 T for improving the surface quality. When 0.26 T was needed to suppress the jet flow and the two re-circulating flows, the velocity beneath the meniscus keeps a more suitable magnitude than that in EMBR mold, which is beneficial to prevent the solidification of the meniscus.

Acknowledgments

This study was supported by the National Natural Science Foundation of China under the contracts No. 50176022.

Nomenclature

- $E$: Electric field intensity (V/m)
- $H$: Magnetic field intensity (A/m)
- $\mu$: Magnetic permeability (H/m)
- $\varepsilon$: Permittivity (F/m)
- $J_a$: Induced current by AC current (A/m$^2$)
- $J_b$: Induced current by DC current and movement of liquid metal (A/m$^2$)
- $J_s$: Coil current for static magnetic field (A/m$^2$)
- $F$: Electromagnetic force (N/m$^3$)
- $B$: Magnetic flux density (T)
- $P_m$: Magnetic pressure (Pa)
- $P_g$: Hydrostatic pressure (Pa)
- $P_s$: Pressure due to surface tension (Pa)
- $H_t$: Tangential magnetic field intensity on the meniscus (A/m)
- $\varphi$: Electrical potential (V)
- $\Gamma$: Surface tension coefficient
- $\sigma$: Electrical conductivity (S/m)

Subscripts

- $a$: Induced by AC current
- $b$: Induced by DC current

Superscripts

- $\rightarrow$: Vector

REFERENCES

1) Y.-S. Hwang, P.-R. Cha, H.-S. Nam, K.-H. Moon and J.-K. Yoon: ISIJ Int., 37 (1997), 659.
2) H. Tozawa, H. Kitaoka, K.-I. Sorimachi, H. Ishizuka, M. Ohnishi and S. Kakkahara: Proc. of the 6th Int. Iron and Steel Cong., ISIJ, Tokyo, (1990), 438.
3) P.-R. Cha, Y.-S. Huang, H.-S. Nam S.-H. Chung and J.-K. Yoon: ISIJ Int., 38 (1998), 403.
4) T. Toh, E. Takeuchi and M. Hojo, H. Kawai and S. Matsumura: ISIJ Int., 37 (1997), 1112.
5) Z.-D. Qian, B.-W. Li, J.-C. He and G.-L. Jia: J. Northeastern Univ., 22 (2001), 79.
6) Z.-D. Qian, B.-W. Li, D.-H. Li, E.-G. Wang and J.-C. He: Acta Metall. Sin., 11 (2001), 1.
7) Z.-D. Qian, B.-W. Li, G.-L. Jia and J.-C. He: ISIJ Int., 41 (2001), 683.
8) A. Tafove and M. E. Brodwin: IEEE Trans. Microwave Theory Techniques, 23 (1975), 623.
9) A. Tafove, K. Umaoharap and T. G. Jurgens: Antennas and Propagation, 33 (1985), 662.
10) O. P. Gandhi and J.-Y. Chen: Bioelectromagnetics Supplement, 1 (1992), 43.
11) M. D. Santis and A. Ferretti: ISIJ Int., 36 (1996), 673.
12) Z.-D. Qian, B.-W. Li, E.-G. Wang and J.-C. He: J. Northeastern Univ., 23 (2002), 553.