3-D Free Surface Simulation in the Electromagnetic Dam

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A method to study the physical phenomena of the molten metal under the AC magnetic field has been required to design the electromagnetic (EM) dam system. This confines a side of the molten metal by Lorentz force without contact between the side wall and the molten metal. In this work, we have developed a numerical analysis method to predict the 3-D phenomena of the molten metal considering the free surface. To evaluate steady the state of the molten metal including the free surface, the integrated computational errors are eliminated after certain iteration step. This process avoids the solution diverged and provides the converged steady state solution. However, although the error elimination process neglects the physical phenomena of smaller scale than the elimination time step related, this method could predict slowly varying the surface shape obtained by the experiment. By using this method, the effects of magnetic field direction and the EM boundary condition on the surface shape are investigated. The profile of Lorentz force corresponding to the direction of magnetic field and boundary condition was found to affect the flow pattern resulting in the change of the steady state surface shape.

KEY WORDS: electromagnetic field; Lorentz force; eddy current; free surface; electromagnetic dam; molten metal; edge element; volume of fluid; simulation.

1. Introduction

Use of electromagnetic (EM) dam plays a major role in the evolution of the steel industry.^{1,2)} The molten metal is pushed away from a side wall by Lorentz force under the AC field, so that both the life extension of the side wall and the purification of products with less contamination could be achieved.

The AC magnetic field applied parallel to the surface of molten metal inside the conductive pot, induces the eddy current interacting with the original magnetic field, which generates Lorentz force to push the surface away from the side wall.³⁾ The surface shape is changed by Lorentz force, accordingly the EM field profile changes near the surface. Thus these phenomena interacting the EM field and the flow field with the free surface are quite complex. In the equilibrium state, the EM pressure, the hydrostatic pressure, and the hydrodynamic pressure are balanced at the surface.

It is required to form the free surface with lower power loss in order to make this technique possible. Because the edge of the conductive pot is also exposed by the EM field, the eddy current loss at the conductive pot could not be ignored.¹⁾ To design a commercial scale EM dam system, the computational technique, which predicts and explains physical phenomena, has been necessary. The EM and the fluid field considering the free surface shape should be coupled in a calculation. However, it has been taken enormous computing time to calculate the complete and precise interac-

tive phenomena (especially, the iteration of 3-D EM field calculation). An alternative way called shadow method was proposed⁴⁾ to reduce the computing time, which calculates Lorentz force considering the free surface transition based on the analytical approximation. In the shadow method, new Lorentz force is evaluated as a function of clearance between the coil and the molten metal with one numerical calculation of the EM field at the first stage. This method is suitable for a simple system consisted of the coil and the molten metal without the core or the conductive pot. When the core or the conductive pot is set in a system, it is difficult to evaluate accurate 3-D Lorentz force distribution by the shadow method. In such a system, the numerical calculation is required to consider the 3-D boundary conditions with time varying free surface.

A 2-D model has been developed⁵⁾ in which the field calculations have been coupled completely with the free surface shape and the dynamic effect of the molten metal flow in a coreless induction furnace. Although the 2-D model is suitable for calculating within shorter computing time, the simple extension of this model to the 3-D system needs enormous computing time to obtain steady state.

Another author⁶⁾ approximately calculated the surface shape of the molten metal in the cold crucible system. EM-field is estimated as the surface of the molten metal changes. However, the balance of the steady EM pressure and the hydrostatic pressure evaluated the surface shape of the molten metal without considering dynamical behavior caused by the flow of the molten metal. The EM field was

calculated by the 3-D finite elemental method (FEM) with edge elements. The method with edge elements⁷⁾ takes significantly less computing time than the traditional method with nodal elements, which could be utilized in a new model. Cha and Hwang⁸⁾ predicted the surface shape of the EM slab caster with the similar 3-D method using the iteration of EM calculation. However, the effect of hydrodynamic pressure was not taken into account to evaluate the surface shape.

Numerical computational method for the free surface of the fluid flow is classified into two groups. The first is to use self-adjusting grids. For example, Evans and Kageyama⁹⁾ simulated the free surface of the EM casting by ALE (Arbitrary Lagrangian-Eulerian) method. This method would not be suitable, if the surface shape changes significantly or folds over itself. The second is the static grid method called VOF (Volume Of Fluid). In this method, the significant surface change could be handled, but smearing of the surface due to the numerical diffusion is occasionally a problem. Kohno *et al.*¹⁰⁾ applied this method to calculate the simple 3-D free surface system with the EM field. This level set method, which reinitialize the free surface shape every certain interval, could be used to prevent smearing of the surface.

Most of these numerical computational methods have calculated the coreless induction furnace without the conductive pot. Some numerical results with the core and the conductive pot have published,¹¹⁾ but the iteration between the EM and the fluid field has not been included. Therefore, the main aim of this work is to develop a numerical calculation method for the 3-D EM dam system with the complete EM and fluid coupling applying the level set method to VOF and to clarify the physical phenomena of the molten metal.

2. System Layout

Figure 1 shows an EM-dam system. The AC magnetic field, which is generated by the AC coil current with the high permeability core, is applied parallel to the molten metal surface (The coil is not shown in Fig. 1). The magnetic field induces the eddy current on the surface of molten metal, which interacts with the original field. This interaction induces Lorentz force, which pushes the surface away. There are two options to confine the molten metal inside the conductive pot, one is the horizontal magnetic field and the other is the vertical magnetic field (Figs. 1(a) and 1(b)). Both cases have been tested to investigate the effect of magnetic field direction. Figure 1(c) shows the size of the conductive pot in this work. One side of the pot has open boundary. The triangular cross section type pot shown in Fig. 1(d) was tested to investigate the EM sealing property for more realistic system of the EM dam¹⁾ at which magnetic field crosses over the inclined boundary.

3. Computer Modeling

3.1. Assumptions

The modeling of EM dam was based on the following assumptions:

- (1) Fluids were Newtonian and incompressible;

Fig. 1. EM-dam systems including core and conductive pot: (a) horizontal field system; (b) vertical field system; (c) rectangular pot; (d) triangular pot.

- (2) The material characteristics were constant;
- (3) The electric field induced by the interaction of fluid velocity and the magnetic field was negligible;
- (4) The pressure due to the surface tension could be negligible from the result of order-estimation;
- (5) The temperature distribution in the molten metal was uniform.

3.2. Numerical Modeling

The EM field was calculated by the 3-D FEM with edge elements using the $A-\phi$ method. The fundamental equations are given as follows:

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A \right) = J_o - \sigma \left(\frac{\partial A}{\partial t} + \nabla \phi \right) \quad \dots\dots\dots (1)$$

$$\nabla \cdot \sigma \left(\frac{\partial A}{\partial t} + \nabla \phi \right) = 0 \quad \dots\dots\dots (2)$$

where μ is the magnetic permeability, A is the magnetic vector potential, J_o is the source current density, σ is the conductivity and ϕ is the electric scalar potential.

Since A varies sinusoidally in the EM-dam system, the time derivative of A is replaced by the complex function $j\omega A$, where $\omega = 2\pi f$ (f : frequency). In addition, the matrix of the FEM is solved by the ICCG (Incomplete Cholesky Conjugate Gradient) method.

Lorentz force density F , which is generated by the interaction of the induced currents and the applied magnetic field, is expressed as:

$$F = \sigma \left(\frac{\partial A}{\partial t} + \nabla \phi \right) \times (\nabla \times A) \quad \dots\dots\dots (3)$$

The fluid field calculation was based on Navier-Stokes equation and the equation of continuity for both the air and the molten metal:

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u = -\nabla p + \eta \nabla^2 u + F + \rho g \quad \text{.....(4)}$$

$$\nabla \cdot u = 0 \quad \text{.....(5)}$$

where ρ is the mass density, u is the velocity, p is the pressure, η is the viscosity and g is the gravitational acceleration.

The 3-D transient finite-volume solution algorithm is selected with well known $k-\varepsilon$ model for the turbulence modeling.

The scalar value called VOF (Volume of Fluid) was used for the free surface modeling. The mass density of each calculative cell for two fluid layers (air and molten metal) is:

$$\rho = \rho_1(1-C) + \rho_2 C \quad \text{.....(6)}$$

where ρ_1 is the mass density of air, and ρ_2 is the mass density of molten metal. C is a scalar value called VOF, which expresses the volume ratio, defined as follows:

$$C = \frac{V_2}{V_1 + V_2} \quad \text{.....(7)}$$

$$0 \leq C \leq 1 \quad \text{.....(8)}$$

where V_1 is the volume of air and V_2 is the volume of molten metal.

The transport equation is described as follows under the assumption of constant density of both fluids:

$$\frac{\partial C}{\partial t} + \nabla C u = 0 \quad \text{.....(9)}$$

3.3. Coupling Methods

The flow chart of this model is shown in **Fig. 2**, which is developed to integrate the 3-D calculations of the EM field, the fluid field and the free surface shape of the molten

Fig. 2. The flow chart of the coupling method between EM and fluid field calculation: where Time is the transient time for simulated scale; Iter is an integer to count the number of iterations of the EM calculation; Δt is the time step size for fluid calculation; and N is a constant integer which is the number of steps of fluid calculation per one EM calculation.

metal. The UNIX shell script was created to run two commercial software packages (MAGNA from CRC Solutions Corp., Japan, for the EM field calculation, and STAR-CD from CD-adapco Japan Corp., for the fluid flow calculation).

The EM field calculations are repeated every N -step transient fluid calculation, which results in the reduction of computing time. N is determined as such, the surface shape slightly changes during N -step fluid calculation. Lorentz force F is evaluated from the last EM calculation result F_0 by using the value of VOF, which enables as to estimate the force acting on the surface:

$$F = CF_0 \quad \text{.....(10)}$$

To evaluate the surface shape for the next EM calculation after N -step fluid calculation, the value of VOF is reinitialized in each cell as:

$$\begin{aligned} C &= 1.0 & (\text{if } 0.5 \leq C) \\ C &= 0.0 & (\text{if } C < 0.5) \end{aligned} \quad \text{.....(11)}$$

This re-initialization is similar to the level set method,¹⁰⁾ however this method is much simpler, just setting new C values. The re-initialization eliminates integrated computational errors, which prevents diverging or smearing the surface of molten metal. However, it should be noted that re-initialization neglects the physical phenomena, which are smaller scale than the elimination time step related. Therefore, the validity of this re-initialization process should be confirmed by the experimental data.

Figure 3 shows typical grids of EM dam with the vertical magnetic field. Half of the region is calculated under the symmetrical condition. The EM region is divided properly with tetrahedral elements including the air region. The cells that would include the free surface are divided into smaller grids. These smaller grids could deal with the skin depth effect. The fluid region could be simply divided with hexagonal elements. To share the data of Lorentz force and the free surface position between the EM and fluid calculation, the data-mapping method is used, in which each grid of fluid calculation takes the value of Lorentz force from a grid of EM calculation that covers the center of the grid of fluid calculation.

3.4. Computational Setup

The calculations were carried out using Silicon Graphics server, Origin 3000. Conditions of the applied field and the physical properties of materials are listed in **Table 1**. The parameters of EM dam are listed in **Table 2**.

4. Experimental Conditions

The experiment was carried out to verify the computational results. The apparatus of the EM dam is shown in **Fig. 4**. Either horizontal (**Fig. 4(a)**) or vertical (**Fig. 4(b)**) field was applied by rotating magnet. The U-Alloy 70 from Osaka Asahi Metal Ltd, Japan was used for the molten metal because of its low melting temperature, 70°C. The components of the U-Alloy 70 are Bi (50%), Pb (27%), Sn, Cd, and In. The temperature of copper pot was controlled to be constant around 80°C by circulating hot water. Insulator for the dam-side wall was necessary to prevent the leakage

Fig. 3. Typical grids of EM dam with vertical magnetic field for the rectangular pot: (a) grid for EM calculation; (b) grid for fluid calculation.

Table 1. Conditions of computational setup.

Coil	Operating current	(A·turns)	4500
	Frequency	(kHz)	10
Core	Material		Silicon steel sheets
	Electric conductivity	(S/m)	0.0
	Relative permeability	(·)	150
Pot	Material		Copper
	Electric conductivity	(S/m)	5.00×10^7
	Relative permeability	(·)	1.0
Air	Material		Air
	Electric conductivity	(S/m)	0.0
	Relative permeability	(·)	1.0
	Mass density	(kg/m ³)	1.205
Molten metal	Viscosity	(kg/ms)	1.81×10^{-5}
	Material		U-Alloy 70
	Electric conductivity	(S/m)	1.06×10^6
	Relative permeability	(·)	1.0
	Mass density	(kg/m ³)	9700
	Viscosity	(kg/ms)	1.86×10^{-3}

Table 2. Parameters of EM dam.

	EM-field direction	Pot type	Initial pool height (mm)
Case1	Vertical	Rectangular	50
Case2	Horizontal	Rectangular	50
Case3	Vertical	Triangular	40

of molten metal when the EM field was off. Silicon steel sheets were used for the core material that was temperature-controlled by water-cooled copper plates.

The shape of the surface was measured by two methods. The thermo sensible paper, which changes color at certain temperature, was used, inserting into the molten metal. The surface profile was clearly obtained as the pattern on this paper. This first method could be used for the horizontal EM field (vertical eddy-current field). For the vertical EM field, the insulation paper insulates the horizontal eddy current. Another method is to use a foil made of the same material as the molten metal. The foil inserted melts leaving outside of the molten metal and the surface shape was ob-

(a)

(b)

Fig. 4. Side view of the experimental apparatus of EM dam: (a) horizontal setup; (b) vertical setup.

tained.

In all cases, the EM dam was conducted at 10 kHz and 4 500 ampere-turns shown in Table 1. The experimental parameters were set as shown in Table 2.

5. Results and Discussion

5.1. Computing Time

100 iterations of EM calculations were repeated until it is converged. The EM field calculation has been repeated every 20-step of fluid calculations, where the time step Δt

Table 3. Number of grids and computing time.

	Number of grids for EM calculations			For fluid calculations		CPU time (hours)		
	Nodes	Cells	Edges	Nodes	Cells	EM	+	Fluid
Case1	18819	105594	126713	40824	36517	80	+	5
Case2	18854	106508	127431	40824	36517	80	+	5
Case3	16324	90694	109284	46805	42930	60	+	7

Computer used: SGI Origin3000

Fig. 5. Typical calculated result of time evolution of 3-D surface shape in Case 1.

was fixed 0.001 s. The number of grids and total computing time for 100 iterations are listed in **Table 3**. One calculation step of the EM field takes about 48 (Case 1 and Case 2) or 36 (Case 3) minutes, resulting 80 or 60 h for total computing time for 100 iterations. By use of the edge-element method for the EM calculation, the computing time becomes shorter comparing with many iterations of other 3-D calculation. The computing time for the fluid calculation is much shorter for each step.

5.2. Time Evolution of Surface Shape

Figure 5 shows typical calculation results of the time variation of 3-D fluid including the surface shape for Case 1. A wave induced by the initial Lorentz force is simulated traveling on the surface of molten metal. The steady state shape is obtained in 2 s when the wave becomes weaker. The time variation of the molten metal surface height at Point A and Point B, which are indicated in **Fig. 5(g)**, is shown in **Fig. 6**. Point B is defined as the contact point on the symmetry plane. From the figure, it is confirmed that the system is converged and reached to be steady up to 2 s.

Fig. 6. Time variation of molten metal height in Case 1 at Point A and Point B that are indicated in **Fig. 5(g)**.**Table 4.** Qualitative comparison of the physical phenomena in Case 1 and Case 2.

	Case1	Case2
Direction of Magnetic field	Vertical	Horizontal
Direction of Eddy current	Horizontal	Vertical
Eddy current in conductive pot	Small	Large
Eddy current in molten metal	Large	Small
Lorentz force in molten metal	Large	Small
No-contact height	High	Low
Power loss in conductive pot	Small	Large
Vertical gradient of Lorentz force	Large at middle	Small at top
Flow pattern	Two loops	One loop

5.3. Effects of Magnetic Field Direction

The effects of magnetic field direction and the EM boundary condition are investigated in detail. The simulated EM and fluid field distributions in Case 1 and Case 2 are compared with each other. The qualitative comparison is summarized in **Table 4**.

5.3.1. No-contact Height

Figures 7(a) and **7(b)** show calculated and measured surface shapes on the symmetry plane with different magnetic field direction for Case 1 and Case 2. Calculated results satisfactorily agree with the measured results. Some discrepancies were occurred in Case 2, which was considered some errors due to the instability at Point B or measurement error. No-contact height is defined as the difference between the height of Point A and Point B. As for the comparison between Case 1 and Case 2, it is found that the no-contact height in Case 1 is higher than that in Case 2 in spite of the same coil current condition. This means that vertical magnetic field is more desirable to achieve higher no-contact height.

Fig. 7. Quantitative comparison between calculated and measured steady state surface shapes in Case 1 and Case 2.

Fig. 8. Steady state distributions of magnetic flux density and eddy current density in Case 1 and Case 2.

5.3.2. Magnetic Flux and Eddy Current

The left side of Fig. 8 shows the distribution of the magnetic flux density in the molten metal and upper air region in Case 1 and Case 2. The magnetic flux concentrates along the molten metal surface by the skin effect. The right side of Fig. 8 shows the distribution of the eddy current density in the conductive pot. The eddy current flows perpendicular to the magnetic flux. Therefore the direction of eddy cur-

rent at the edge of conductive pot is horizontal in Case 1 and vertical in Case 2. The maximum value in Case 1 (3.1×10^8 A/m²) is much smaller than that in Case 2 (4.9×10^8 A/m²). In Case 2, the eddy current is easier to flow, because the direction of the edge of the conductive pot boundary is the vertical direction, which is same as eddy current direction. On the other hand, in Case 1, there is a horizontal discontinuous boundary condition of eddy cur-

Fig. 9. Steady state distributions of Lorentz force density and flow velocity in Case 1 and Case 2.

rent at the interface of the conductive pot edge when the molten metal is pushed away. This means that Lorentz force profile generated by AC magnetic field is affected by the electric boundary condition through eddy current profile.

5.3.3. Lorentz Force and Flow Pattern

The left side of Fig. 9 shows the distribution of Lorentz force density in the molten metal in Case 1 and Case 2. The maximum value is $2.0 \times 10^6 \text{ N/m}^3$ in Case 1, and $1.0 \times 10^6 \text{ N/m}^3$ in Case 2. The force in Case 2 is smaller than that in Case 1, because the eddy current is mainly focused on conductive pot in Case 2 shown in Fig. 8, reducing the eddy current in the molten metal. This calculation agrees with the result of higher no-contact height in Case 1 than that in Case 2. The power loss at the conductive pot in Case 1 is lower than that in Case 2 because the eddy current in Case 1 is smaller than that in Case 2. Thus, the vertical magnetic field is superior to the horizontal field on high no-contact height with lower power loss.

The vertical gradient of Lorentz force greatly affects the flow pattern of the molten metal. In Case 1, the eddy current in the molten metal has horizontal profile, which is relatively reduced at the bottom of the metal pool. This reason is considered as such, the part in the conductive pot near the bottom of the metal pool is the easiest part to flow for

the eddy current. Lorentz force is also reduced at the upper part of the surface, because of the distance between the magnet and the molten metal surface, which is pushed away. The result of Case 1 shows that Lorentz force is large in the middle height of the pool. As for in Case 2, the vertical gradient of Lorentz force is almost uniform except the upper part where the molten metal is pushed away. Fluid flow velocity distributions in Case 1 and Case 2 are shown on the right side of Fig. 9. The flow directions along the molten metal surface are directed from a small part of Lorentz force to a large part. In Case 1, two different rotating loops are formed. This might be caused by the vertical gradient of Lorentz force that is large in the middle height. The confluent point of two loops is near the contact point between the molten metal and the wall of dam side. This point might be limiting the no-contact height. As for the flow pattern in Case 2, one-loop flow from the top to the bottom on the surface is formed due to the vertical gradient of Lorentz force. The flow from the conductive pot side to the symmetry side is also formed due to the horizontal gradient of Lorentz force. These results indicate that the profile of Lorentz force is important for flow pattern, which might be affecting to the surface stability.

Fig. 10. Calculated and experimental results in Case 3: (a) comparison between the calculated and measured steady state surface shape on the symmetry plane; (b) top view of the calculated 3-D steady state surface shape; (c) top view of the observed 3-D surface shape in the experiment.

5.4. Triangular Cross Section

The triangular cross section pot type with the vertical magnetic field was also tested in Case 3. The results are shown in **Fig. 10**. Figure 10(a) compares the calculated and measured surface shape on the symmetry plane in Case 3. The calculated shape matches quite well with the experimental measurement. No-contact height in Case 3 is obtained as high as in Case 1. The 3-D shape in Case 3 was compared qualitatively in Figs. 10(b) and 10(c). The 3-D calculated shape from the top view has good agreement with the experimental camera view. The calculation method in this work is also verified for the general system of EM dam with the inclined pot boundary.

6. Conclusion

A numerical analysis method to predict the 3-D phenomena of the molten metal considering the free surface in the EM dam has been developed. 3-D surface shapes were simulated and the steady state surface shape was obtained by eliminating the integrated computational errors after certain iteration step. The calculated surface shapes matched well with the experimental results. By using this method, it has been made possible to study the change of surface shape according to control parameters. The direction of the applied magnetic field greatly affects to the eddy current profile at the conductive boundary. The vertical magnetic field

was found superior to the horizontal field on resulting in high no-contact height and less power loss. The gradient of Lorentz force affects the flow pattern of the molten metal, which might be limiting no-contact height. The vertical magnetic field is also effective to keep high and stable no-contact height for different cross section of molten metal.

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