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EFFECT OF INNOVATIVE CATHODE ON BATH/METAL INTERFACE FLUCTUATION IN ALUMINUM ELECTROLYTIC CELL

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Abstract

A three-dimensional transient magnetohydrodynamic model has been developed to investigate the effect of innovative cathode on interface fluctuation of bath/metal in aluminum electrolytic cell. A homogeneous multiphase flow model of three phases including molten aluminum (metal) and molten cryolite (bath) using the volume of fluid (VOF) approach is used to describe phases interaction. Moreover, the electrical potential method is adopted for the electric current and magnetic field. The Electromagnetic force is recalculated at each time step and then is implemented in the momentum equation of bath and metal as a source term. Then the mathematical model is employed to investigate the effect of the innovative cathode on the electric current, magnetic field, flow field, and bath/metal interface fluctuation. The results show that the interface fluctuation would be suppressed with the help of innovative cathode. In addition, the gas bubbles also float up more quickly which is good to energy saving.

Introduction

The Hall-Héroult process is the main industrial process for the production of primary aluminum. Alumina powder is dissolved in the bath. A direct current is applied and passes through the entire reduction cell. In this process, the interaction of magnetic field with the current produces an EMF which causes fluctuation of the molten fluid. In addition, because of the electrochemical reaction, carbon monoxide and carbon dioxide form at the bottom of the anode, and induce molten fluid motion in the process of floating up to escape. Thus, the molten fluid motion is due to the combined effect of the EMF and the gas bubbles generated at the anode.

The process of aluminum electrolysis costs lots of electric energy. Stable and efficient operation of the electrolysis process involves the removal of anode gas bubbles and the oscillation of the metal-bath interface. Many researchers have been made to study the interface deformation. Severo et al. [1] developed a 3-D model by coupling commercial software ANSYS and CFX. By using the homogeneous model, they calculated the flow field and interface deformation of metal. But they ignored the anode gas bubbles that also contribute to the interface deformation. Li et al. [2] studied the flow characteristics and the vortex structures of the molten fluid in the aluminum reduction cell by using the method of vorticity and swirling strength. The results reveal that, compared with velocity vector distribution and streamline picture, this method can provide more flow field information. Vortexes usually occur as reverse symmetrical pairs. The single factor comparative study shows that the EMF tends to trigger large vortexes near the upstream side, while gas bubbles mainly stir the bath and generate small vortexes.

Recently a low energy consumption aluminum reduction cell with novel protrusion, as show in Figure 1, was proposed by Feng [3]. The results of industrial experiments showed that the electric power is reduced by more than 1200 kWh for every ton of aluminum with the help of this novel cathode. In this paper, the electromagnetic field and melt flow-related phenomena in the new reduction cell with novel protrusion was studied using a coupled mathematical model. This paper provides the theoretical basis for the optimization of the novel cathode.

Figure 1.Aluminum reduction cell with innovative cathode.

Figure 2.Computation domain in present work.

Mathematical Model

The computation domain used in present work is shown in Figure 2. The well know $\varphi - \vec{A}$ approach is to solve the electromagnetic field in the melt [4]. It is constitute of simultaneously solving the electric potential φ as well as magnetic potential vector $\vec{A}$ equations. The electric potential equation is extracted from the conservation of the electric current:

$$\vec{B} = \nabla \times \vec{A} \text{ and } \vec{E} = -\nabla \varphi - \frac{\partial \vec{A}}{\partial t} \tag{1}$$

In general, Ohm's law that defines the current density is given by:

$$\vec{J} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right) \quad (2)$$

A parameter that can be used to evaluate the relative predominance of one mechanism of magnetic field transport over the other is magnetic Reynolds number (magnetic equivalent of the ordinary Reynolds number) which is defined as:

$$Re_m = u_0 L_0 \sigma \mu_0 \quad (3)$$

If Re_m is less than one, the diffusion transport of the magnetic field dominates over the convective transport. The Re_m in the aluminum electrolysis process is supposed to be less than one. Thus, the magnetic field in ESR process is mainly transported by diffusion and the Equation (2) can be simplified as:

$$\vec{J} = \sigma\vec{E} \quad (4)$$

In addition, the magnetic flux density (mT) induced by the bus bar can be expressed as follows:

$$B_x = 6.0y \quad (5)$$

$$B_y = -3.0x + 1.5 \quad (6)$$

$$B_z = 1.0xy + 0.5 \quad (7)$$

The EMF can be decomposed into a time-dependent component and a time-independent component when the harmonic electromagnetic force is considered. Numerical studies on the electromagnetically driven flow show that the alternating current period which control the variation period of the electromagnetic field is much shorter than the momentum response time of the liquid metal if its frequency is large than 5Hz. Therefore, the time-averaged electromagnetic force is expressed as follows [5]:

$$\vec{F}_e = \frac{1}{2}\mathrm{Re}\left(\vec{J} \times \vec{B}^*\right) \quad (8)$$

The fluid flow is modeled with the time-averaged Navier-Stokes equation. The RNG *k-ε* turbulence model which is derived using renormalization group theory is adopted to consider the turbulent flow in the aluminum electrolysis process. While the standard *k-ε* turbulence model is for a high Reynolds number fluid flow, the RNG *k-ε* turbulence model provides a more comprehensive description for high as well as low Reynolds number fluid flow with an appropriate treatment of the near-wall region.

The interface between the metal and slag is tracked with the geometric reconstruction VOF approach proposed since it is a robust, powerful, extensively applied technique. An important parameter–the volume fraction of fluid per cell α is solved simultaneously. It is defined as the integral of a cell. Basically, when the cell is empty (no traced fluid), the value of α is 0. If the cell is full, the value of α is 1, and when the interface cuts the cell, α is a number between 0 and 1. During the calculation, the fluid volume fraction in each cell is consistent with the resolution of the other flow quantities. If the amount of fluid in each cell is known, then it is possible to locate the interface, as well as determine the interface slope and curvatures. The interface can be located because they lie in cells partially filled with fluid or between cells full of fluid and cells that have no fluid. A single set of governing equations is shared by the metal and slag. Moreover, the physical properties appearing in the governing equations are determined by the presence of the component phase in each control volume. Surface tension arises as a result of attractive forces between molecules in a fluid. The surface tension is supposed to play an important role on the falling droplet as well as the oscillation of slag/metal interface. The continuum surface force model is implemented to consider the surface tension [6].

Results and Discussion

It is necessary to validate the mathematical model. Figure 3 shows the comparison between the experiment in reference [7] and the computation. A good agreement can be observed obviously. The maximum deviation between experiment and computation is less than 5%.

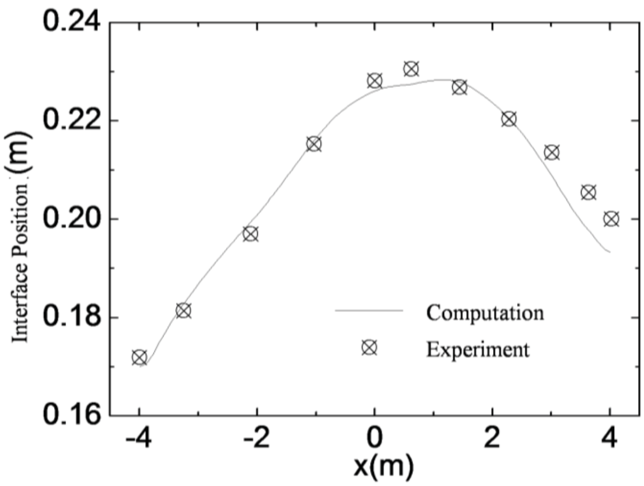

Figure 3.Comparison between the experiment and computation.

Figure 4 shows the deformation of bath/metal interface in the cell with traditional cathode under the EMF which generated by the horizontal magnetic flux density and vertical current. The central of the interface is humped. Moreover the maximum height of hump is 24mm, and the maximum sinking is 40mm. Figure 5 shows the velocity field at the metal pad in the cell with traditional cathode. Four big vortexes are observed clearly, and the two vortexes at the left side are much stronger than the two vortexes at the right side.

The interaction between the current and magnetic flux density would generate the EMF which forces the melt flow, and in turn, the melt flow would also affect the current field. Therefore, it is possible to suppress the melt flow in the cell in order to save energy.

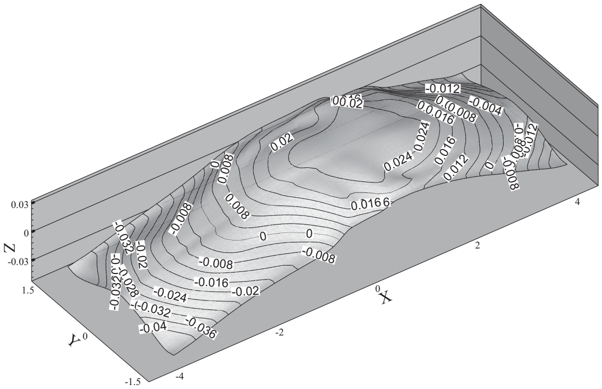

Figure 4.Deformation of the bath/metal interface in the cell with traditional cathode.

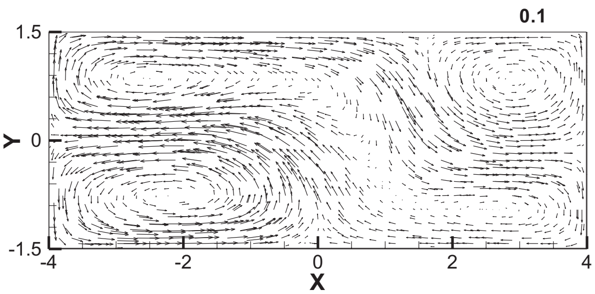

Figure 5.Velocity field at the metal pad in the cell with traditional cathode.

Figure 6 shows the deformation of bath/metal interface in the cell with innovative cathode under the EMF. The central of the interface is humped which is similar to the phenomena in the cell with traditional cell. However, the maximum height of hump is only 15mm, and the maximum sinking is 38mm which decreases 37.5% and 5% relative to the deformation in the cell with traditional cathode, respectively. Therefore, the oscillation of the interface is suppressed obviously in the cell with innovative cathode. The anode-cathode-distance (ACD) can be also decreased which is good to the energy saving. Figure 7 shows the velocity field at the metal pad in the cell with innovative cathode. Four big vortexes are also observed clearly, and the two vortexes become stronger than that in the cell with traditional cell.

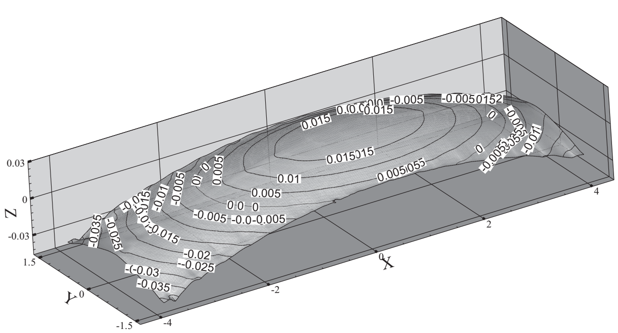

Figure 6.Deformation of the bath/metal interface in the cell with innovative cathode.

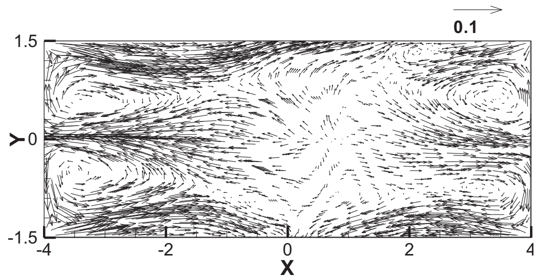

Figure 7.Velocity field at the metal pad in the cell with innovative cathode.

Figure 8 shows the comparison of the interface deformation in the cell with traditional cathode and innovative cathode. It is easy to find the oscillation of the bath/metal interface in the cell with innovative cathode is gentler than that in the cell with traditional cathode. Therefore, we can decrease the ACD in the cell with innovative cathode in order to save energy.

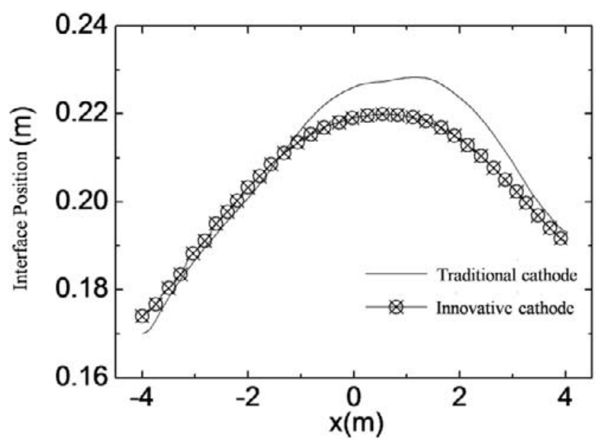

Figure 8.Height of the bath/metal interface at the middle line.

Conclusions

1) A three-dimensional transient magnetohydrodynamic model has been developed to investigate the effect of innovative cathode on interface fluctuation of bath/metal in cell. The VOF approach is used to describe the multiphase flow. Moreover, the electrical potential method is adopted for the electric current and magnetic field. The Electromagnetic force is recalculated at each time step and then is implemented in the momentum equation of bath and metal as a source term.

2) The oscillation of the bath/metal interface is suppressed clearly in the cell with innovative cathode. The ACD can be decreased in the cell with innovative cathode which is good to the energy saving.

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