NUMERICAL MODELLING OF MELTS FLOW AND INTERFACE DEFORMATION IN ALUMINIUM REDUCTION CELLS

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Summary A modelling approach with coupling of a CFD based transient multiphase flow model (VOF method) and an electromagnetic model is developed to predict the melts flow and interface deformation in aluminium reduction cells. The performance of the proposed approach is evaluated by applying it to a simplified box model and a real-scale box model for reduction cells. The simulation results demonstrate its potential for predicting the metal heaving for industrial applications.

INTRODUCTION

In an aluminium reduction cell, the electrochemical reduction occurs inside the molten electrolyte layer (bath), which is floating on top of the liquid metal layer (metal) due to density difference. Electromagnetic forces lead to a steady movement of the two superimposed liquids and a deformation of the metal-bath interface limiting both current and energy efficiency of the reduction cell [1], and hampering process control. In addition, harmful process disturbing metal-bath interface instabilities coupled to the background flow and metal pad deformation can occur. Accurate prediction of both the melts flow and the bath-metal interface deformation [2] is therefore critical for the design and operation of aluminium reduction cells. To achieve this, a multiphase flow model (VOF method) is used to predict the liquid flows and track the deformation of bath-metal interface, which takes into account the effect of the Lorentz force field. The Lorentz force field is calculated using an electromagnetic model. A Laplace equation is solved for the electrical potential, from which the electric current density can be derived. With the electric current density distribution and a predefined magnetic field, the Lorentz force field can be calculated. Hence, the current model considers directly the coupling among liquid flow, interface deformation, electrical potential, current density distribution and the Lorentz force.

MATHEMATICAL FORMULATIONS

Governing equations for the VOF method

The Volume of Fluid (VOF) method can be used to simulate the dynamics of a two immiscible fluid system by solving a single set of momentum and continuity equations, and track the distribution of volume fraction of each fluid throughout the computational domain. The VOF formulation is generally used to compute a time-dependent solution. The governing equations of the continuity and momentum conservation for a two-phase flow system with incompressible fluids are expressed as

$$\nabla \cdot \mathbf{u} = 0 \quad \text{and} \quad \frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla P + \nabla \cdot [\mu(\nabla \mathbf{u} + \nabla \mathbf{u}^{\boldsymbol{T}})] + \mathbf{F}_E + \rho \mathbf{g} \ , \tag{1}$$

where $\mathbf{u}$ is the flow field, P the pressure, $\mathbf{g}$ the gravitational acceleration and $\mathbf{F}_E$ is the external body force such as the Lorentz force. ρ and μ are the fluid density and effective viscosity, respectively. For a two-fluid system, the fluid properties (ρ and μ) are calculated with fluid volume fraction weighted averaging

$$\rho = \rho_1(1-\alpha_2) + \rho_2\alpha_2 \quad \text{and} \quad \mu = \mu_1(1-\alpha_2) + \mu_2\alpha_2 \ , \tag{2}$$

where the subscripts 1 and 2 are the primary phase and the secondary phase, respectively. α is the fluid volume fraction. The distribution of the volume fraction for each phase and the tracking of the phase-interface are accomplished by solving the continuity equation for the volume fraction of the secondary phase (α_2)

$$\frac{\partial}{\partial t}(\alpha_2) + \mathbf{u} \cdot \nabla \alpha_2 = 0 \ , \tag{3}$$

The primary-phase volume fraction (α_1) will be determined by the phase continuity constraint: $\alpha_1 = 1 - \alpha_2$.
Standard k-ε turbulence model is also solved to calculate the turbulent viscosity in the effective viscosity of each phase.

Electrical potential and Lorentz force field

The Lorentz force is needed to close the governing equations for fluid flow. For ease some simplifications are made in the calculation of the electromagnetic field at this stage: (1) the magnetic field changes due to induction is ignored. And, a predefined magnetic field ($\mathbf{B}$) is input for the calculation of Lorentz force; (2) the electric current induced by the motion of conductive liquid in the magnetic field is also ignored. Hence, the equation for electrical potential distribution in the reduction cell can be simplified as

$$\nabla \cdot \sigma \nabla \varphi = 0 \quad \text{and} \quad \frac{1}{\sigma} = \frac{\alpha_1}{\sigma_1} + \frac{\alpha_2}{\sigma_2} \ , \tag{4}$$

where φ is the electrical potential and σ is the electrical conductivity. A volume fraction weighted harmonic average method is used to calculate the distribution of electrical conductivity in the two-fluid system.

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With the solution of equation (4) for the electrical potential distribution, the electric current density $\mathbf{J}$ is calculated from Ohm's law as $\mathbf{J} = -\sigma\nabla\varphi$. With the predefined magnetic field ($\mathbf{B}$), the Lorentz force is given by $\mathbf{F}_E = \mathbf{J} \times \mathbf{B}$. The calculated Lorentz force is included in the source term ($\mathbf{F}_E$) of momentum equation (1).

SIMULATION RESULTS AND DISCUSSIONS

A simplified box model with multiple anodes and channels

A simplified box model for an aluminium reduction cell as shown in Figure 1(a) is built for studying the numerical approach to solve the coupled governing equations, and investigating the mechanism for bath-metal interface deformation. Here, the magnetic field is assumed as: $B_x = 6.0 \cdot y \cdot 10^{-3}(\mathrm{T})$, $B_y = -6.0 \cdot x \cdot 10^{-3}(\mathrm{T})$, $B_z = (x \cdot y + 0.5) \cdot 10^{-3}(\mathrm{T})$. The electrical potential on the anodes is set to zero, and the out-normal current density applied on the cathode is set to $10^4 \mathrm{A/m^2}$. Figure 1(b) shows the current density distribution on the cutting planes of the reduction cell model. The current density is strongly affected by the distribution of the channels between the anodes and cell walls. The current density in channels is relatively low in the bath layer. Due to the high conductivity of metal, the current density becomes unevenly distributed in the metal layer. The electric current density with different distribution pattern in the metal/bath layers interacts with the magnetic field and an uneven Lorentz force field is resulted. It will result in liquid flow inside each layer and interface deformation. Figure 1(c) shows the distribution of interface height. In general, the metal becomes piled up at in the cell centre. It is also shown that the interface under channels has high deformation, which is due to the high current density difference in the bath and metal layers. Figure 1(d) shows the liquid flow vectors on the interface. A recirculating flow pattern is formed as the result of the Lorentz force distribution.

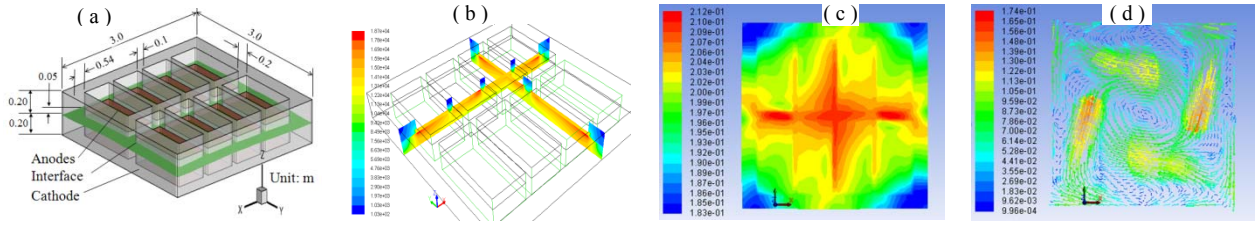

Figure 1 (a) Geometry of the simplified box model for aluminium reduction cell; (b) The electric current density distribution ($\mathrm{A/m^2}$); (c) The vertical position of bath-metal interface (m); (d) Liquid velocity on the interface (m/s).

A real-scale box model for aluminium reduction cell

To extend the proposed modelling to industrial size reduction cells, a real-scale box model as shown in Figure 2(a) is built for investigating the feasibility. The magnetic field is assumed as: $B_x = 6.0 \cdot y \cdot 10^{-3}(\mathrm{T})$, $B_y = (-3.0 \cdot x + 1.5) \cdot 10^{-3}(\mathrm{T})$, $B_z = (x \cdot y + 0.5) \cdot 10^{-3}(\mathrm{T})$. The electrical potential on the anodes is set to zero, and the out-normal current density on the cathode is set as $J_z = (-1700 - 750 \cdot y \cdot y)\ \mathrm{A/m^2}$. The distribution of interface height predicted by the simulation is shown in Figure 2(b). Generally, the bath-metal interface heaves up in the cell centre. Figure 2(c) shows the liquid flow patterns on the interface. It becomes much more complex. A comparison with the predictions by Severo et al. [3] for a similar MHD problem indicates that the simulation results of the current model agree reasonably well.

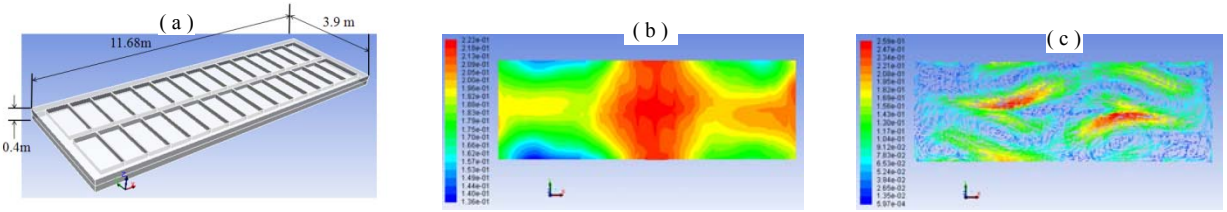

Figure 2 (a) A real-scale box model for industrial aluminium reduction cells; (b) The distribution of bath-metal interface height (m); (c) Liquid velocity (m/s) on the interface.

CONCLUSIONS

A numerical modelling approach is proposed to simulate the melts flow and interface deformation in aluminium reduction cell. The simplified box model is used to test the numerical method and explore the mechanism for interface deformation. And the real-scale box model proves the feasibility of extending the model to industrial size reduction cells.

References

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