Effect of Lorentz Force on Motion of Electrolyte in Magnesium Electrolysis Cell

Cheng-Lin Liu [1], Ze Sun [1], Gui-Min Lu [1], Xing-Fu Song [1], and Jian-Guo Yu [1,2]

[1] National Engineering Research Center for Integrated Utilization of Salt Lake Resource
East China University of Science and Technology, Shanghai, 200237, China
liuchenglin@ecust.edu.cn, zsun@ecust.edu.cn, gmlu@ecust.edu.cn, xfsong@ecust.edu.cn

[2] State Key Laboratory of Chemical Engineering
East China University of Science and Technology, Shanghai, 200237, China
jgyu@ecust.edu.cn

Abstract **–** Magnesium production process is highly energy intensive. Electrolysis process provides an effective route to reduce the energy consumption. In this paper, a three-dimensional electro-magneto-hydro-dynamics coupling model of a 120 kA magnesium electrolysis cell using finite element method is presented. In this model, the electric field, magnetic field, and flow field are included. This paper concerns the effects of the Lorentz force on the motion of the electrolyte in the cell. The model predicts that the magnitude of Lorentz force is at its maximum near the region between the anode and cathode. The direction of the Lorentz force is beneficial to the motion of the electrolyte in the magnesium electrolysis cell.

Index Terms **–** Electro-magneto-hydrodynamics, Lorentz force, magnesium electrolysis cell.

I. INTRODUCTION

Magnesium has found a variety of applications due to a number of advantages including low mass density and high specific strength. Like the Hall-Herault process of aluminum production [1], the electrolysis process for magnesium is one of the most energy intensive industrial processes [2]. Over the years, lots of research efforts have been made on the investigations of the flow field, thermoelectric field, electro-hydrodynamic field, thermoelectromechanical model and magneto-hydrodynamic model by using the commercial software packages [3-7].

Over the years, much attention has been paid on aluminum reduction cell. Little effort, however, has been made on the magnesium electrolysis cell. Shilova and Shcherbinin investigated the distribution of the electromagnetic field with the effects of bus bar and electrode in the magnesium electrolysis cell [8]. The research indicated that the magnetic field will help to improve the circulation and convection of the electrolyte. Recent years some researches on the multi-physical fields including the electric field, magnetic field and flow fields in magnesium electrolysis cells have been reported [9, 10]. In summary, most of the reported studies of magnesium electrolysis cell only considered the mathematical model based on one physical fields. But little progress has been made on the effect of the Lorentz force on the motion of the electrolyte by using a 3D full cell coupling model of electro-magneto-hydrodynamics fields.

This paper presents an Electro-magneto-hydrodynamics model for the magnesium electrolysis cells to investigate the distributions of electric filed, magnetic field and flow field simultaneously. Moreover, the main objective of the article is to show the Lorentz force distribution throughout the cell and its effects on the motion of the electrolyte.

II. DESCRIPTION OF NUMERICAL SIMULATION

A. Structure of magnesium electrolysis cell

In the present article, a 3D full cell model of 120 kA commercial magnesium electrolysis cell with a set top entry of graphite anodes and a set side entry of steel cathodes typically consists of the molten electrolyte of $MgCl_2$, massive refractory lining, thermal insulating materials, asbestos board, steel shell, capping, and partition wall. The structural parameters used in this work have been reported elsewhere and only a brief description will be given here [11].

B. Governing equations

In the electrolysis process, DC current is fed from the anodes, and flow out from the cathodes after passing through the electrolyte. The study consider the electric field, magnetic field and flow field as the main physical fields in the model. To ensure the feasibility of the model, the following hypotheses are made:

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(a) The model only focuses on the resistance voltage without considering the voltage for the decomposition of magnesium chloride, overvoltage, and contact voltage drop in the cell.
(b) Anodes are assumed to share all of the current in cells equally.
(c) All the magnetic line are in the air region.

The problem of electromagnetic analysis is solving Maxwell's equations subject to certain boundary conditions. The Ohm's law is used to predict current distribution as follows:

$$\boldsymbol{J} = \sigma(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}). \quad (1)$$

The Lorentz force of the electrolyte is:

$$\boldsymbol{F} = \boldsymbol{J}\times\boldsymbol{B}. \quad (2)$$

Magnetic induction is used for magnetic flux density calculation as follow:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B}) + \frac{\mathbf{1}}{\sigma\mu}\nabla^2\boldsymbol{B}. \quad (3)$$

$\nabla \times (\boldsymbol{v} \times \boldsymbol{B})$ is negligible in comparison with other terms, and reduces to the following:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \frac{\mathbf{1}}{\sigma\mu}\nabla^2\boldsymbol{B}. \quad (4)$$

On the supposition that the molecular viscous stress tensor can be neglected in comparison with the turbulent stress tensor, the momentum equation is given as follows:

$$\nabla \times \boldsymbol{v} = 0, \quad (5)$$

$$\frac{\partial(\rho \boldsymbol{v})}{\partial t} + (\rho\boldsymbol{v}\cdot\nabla)\boldsymbol{v} = -\nabla p + v\nabla^2\boldsymbol{v} + \rho\boldsymbol{g} + \boldsymbol{F}. \quad (6)$$

The *k*-*ε* model is used for computing velocity profile of electrolyte using the Lorentz forces (***F***) as source term. The *k*-*ε* model is a class of turbulent model, called the two-equation model, where the isotropic eddy viscosity is characterized by the turbulent kinetic energy (k) and its dissipation rate (ε), and the equations can be modified to satisfy no-slip boundary conditions at the walls.

B. Boundary conditions

The Neumann boundary condition is adopted at each top of anodes, with the normalized current density of inward current flow equals to the current intensity divided by the working area:

$$-n\cdot\boldsymbol{J} = \boldsymbol{J_n}. \quad (7)$$

A voltage potential of zero is set at end of cathodes:

$$V = 0. \quad (8)$$

The magnetic vector potential at all of the exterior surfaces of air region is zero:

$$n \times \boldsymbol{A} = 0. \quad (9)$$

The solutions to these equations are carried out by a finite element software of COMSOL. An optimum number of elements were chosen when two consecutive grid refine elements yield an error less than 1% on both magnetic field and Lorentz force calculations.

III. RESULTS AND DISCUSSION

A. Electromagnetic model validation

It is necessary to validate the accuracy of the mathematical model developed in this article, before using them for numerical experiments. The predicted results are validated by an electromagnetic coil. The coils are shown in Fig. 1 and its structure parameters are shown in Table 1.

Table 1: Technical specifications of the original vice coil of 24009 and 24010

Coil Type	Internal Diameter (mm)	External Diameter (mm)	Length (mm)	Wire Diameter （mm）	Number of Coils
24009	42.9	45.1	66.5	0.22	1150
24010	27.0	29.2	51.7	0.22	370

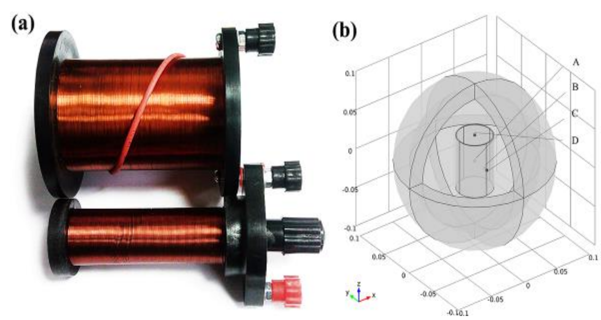

Fig. 1. Electromagnetic coil: (a) experiment, and (b) mathematical model.

The comparison of the magnetic flux density between the experiments and simulations in the position A, B, C, and D of original vice coils are listed in Table 2. Almost all the relative error in the four test points are less than 10%, which shows that the mathematical model can predict the electromagnetic field accurately.

Table 2: Magnetic flux density of experiments and simulations in the different positions of original vice coils

Coil Type	Voltage/V	A/Gs			B/Gs			C/Gs			D/Gs		
		Exp.	Simul.	Relative Error	Exp.	Simul.	Relative Error	Exp.	Simul.	Relative Error	Exp.	Simul.	Relative Error
24009	2.57	47.7	43.6	-8.6%	49.1	43.8	-10.8%	2.5	2.3	-8.0%	9.9	10.8	9.1%
	4.25	77.5	72.2	-6.8%	78.6	72.4	-7.9%	3.5	3.8	8.6%	15.8	17.9	7.8%
	5.92	105.4	100.5	-4.6%	102.6	100.9	-1.7%	5.1	5.3	3.9%	21.9	24.8	8.3%
24010	2.52	70.1	63.2	-9.8%	71.4	63.1	-11.6%	2.1	2	-4.7%	25.2	24.5	-2.8%
	4.19	109.8	104.8	-4.6%	116.2	104.9	-9.7%	3.8	3.4	-10.5%	39.6	40.8	3.0%
	5.84	148.5	146.1	-1.6%	154	146.2	-5.1%	5.3	4.7	-11.3%	54.4	56.9	4.6%

B. Distribution of electromagnetic field

In the magnesium electrolysis cell, current fed from up of the anodes, and flow out from the profile, which form a coil with a quarter of a turn. The magnetic flux density is plotted in Fig. 2. The max of the magnetic flux density is about 270 Gauss (27 mTesla) approximately at the position between the anode and cathode, where is the centre of the "electromagnetic coil". The magnetic flux density of the magnesium electrolysis cell and aluminum reduction cell are at the same order of magnitude [12].

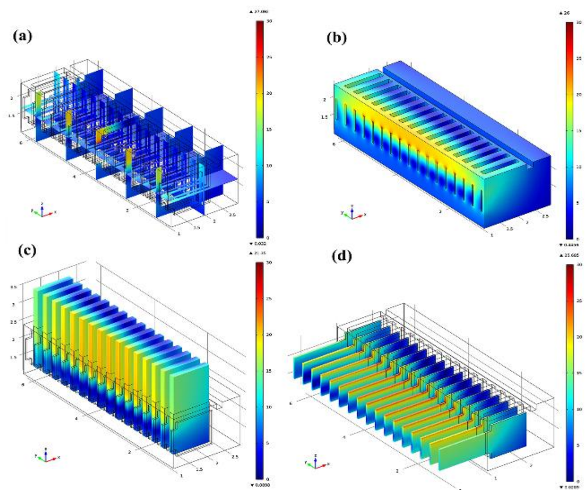

Fig. 2. Magnetic flux density in the magnesium electrolysis cell: (a) slide of electrolyte, (b) electrolyte, (c) anodes, and (d) cathode.

As shown in the Fig. 3, the magnetic flux density in the magnesium electrolysis cell are mainly focused on region between the anode and cathode. The vectors distribution of the magnetic flux density is like a one-fourth of electromagnetic coil.

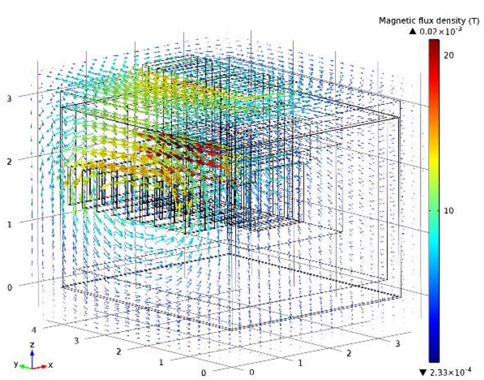

Fig. 3. Vectors of magnetic flux density in the magnesium electrolysis cell.

C. Lorentz force

Lorentz force is an important motive force of the motion of electrolyte in the magnesium electrolysis processing. In Fig. 4, the typical contour and vector plots of the Lorentz force are plotted in the cell. These results show a high Lorentz force appears between the electrodes in the electrolyte, which is because the higher current density and higher electrolyte velocity. The maximum Lorentz force reaching 93.1 N m^{-3} at corner. And the Lorentz force become lesser toward the collection from electrolysis compartment. This will result in a significant velocity gradient in electrolyte, and may have an influence on the overall flow pattern of the electrolyte in the cell. These results show a high Lorentz force between the electrodes, which is because of the higher current in the region.

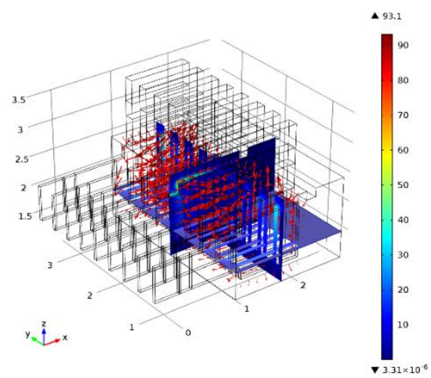

Fig. 4. Lorenz force vectors distribution in the 120 kA magnesium electrolysis cell.

Figure 5 shows the velocity vector and contour plots of the velocity magnitude in the electrolyte of the cell under the effect of the electromagnetic force. The calculated maximum magnitude of the velocity are 0.13 m s^{-1}, at the regions between the electrodes. Velocity decreases toward the center of the cell as the magnetic flux density decreases. The direction of the flow patterns is clearly a function of Lorentz force. Because the Lorentz force is the only volume force in the electrolyte, the motion of the electrolyte in the magnesium electrolysis cell follows the direction of the Lorentz force.

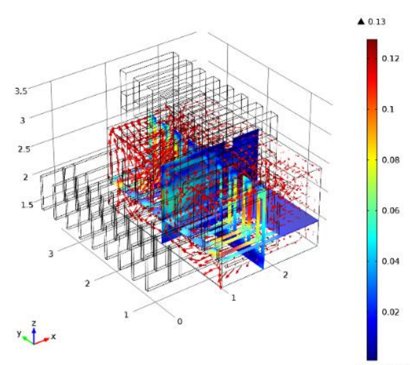

Fig. 5. Velocity vectors distribution in the 120 kA magnesium electrolysis cell.

Figure 6 shows the velocity vector and contour plots of velocity magnitude in the center of the cell (y = 2.05 m). The results show a large vortice with clockwise rotation in the cell. It is note that, the directions of Lorentz forces will help improve the circulation of electrolyte and increase the electrolysis efficiency.

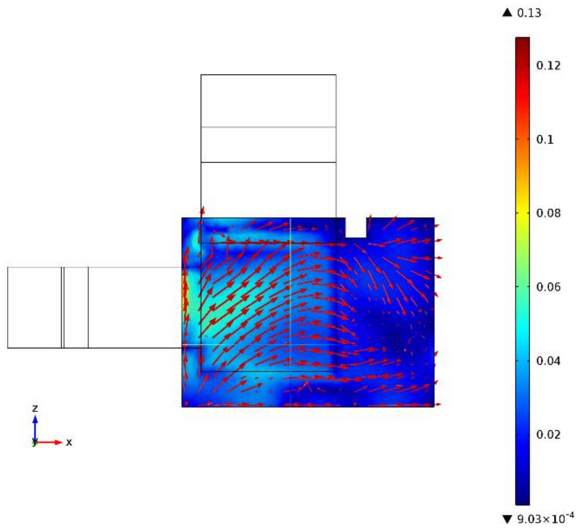

Fig. 6. Velocity vectors and contour plots of velocity magnitude in the center of the cell.

IV. CONCLUSION

A three-dimensional mathematical model of 120 kA magnesium electrolysis cell has been developed using the finite elements method. The electromagnetic field was computed, and its accuracy was validated by an electromagnetic coil. The Lorentz force acting in electrolyte was calculated based on a DC current passing through the cell and the induced magnetic field. On the basis of the electromagnetic field and flow field, the Lorentz force phase was coupled into the electromagnetic field and flow field. The model predicts that the magnitude of Lorentz force is at its maximum near the region between the anode and cathode. The direction of the Lorentz force is beneficial to the motion of the electrolyte in the magnesium electrolysis cell.

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