3-D Numerical Modeling of MHD Flows in an Aluminum Reduction Cell

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Abstract. Three-dimensional numerical modeling of processes in an aluminum electrolytic cell at a current of 9 kA is performed. The model considers the nonlinear temperature dependence of all physical characteristics of materials. The specificity of the work is the inclusion in the model of the dynamics of the gas formed during the operation of the cell. The bubble motion, magnetic forces and heat convection essentially affect the overall dynamics of the electrolyte and metal. Calculations were carried out using the commercial software packages ANSYS CFX 18.2 and ANSYS Maxwell united with the aid of the user FORTRAN program.

1. Introduction

One of the ways to reduce accumulation of the gas on the anode surface is to develop anodes preventing such accumulation. Therefore, when designing new and modernizing existing aluminum cells, it is necessary to predict the effect of the anode gases on their work. However, the known analytical dependencies, obtained by theoretical and experimental methods, are difficult to use for practical purposes. The available equations for determining the voltage drop and the thickness of the gas layer on the anode surface include many unknown parameters of the cell operation and allow only a rough estimation. Determining the effect of gas flow in the electrolyte on the general state of the work element using analytical dependencies is impossible. In order to determine the effect of anode gases on the cell voltage and electrolyte movement, a mathematical model was developed in the present work that takes into account convection, heat transfer, and electrical conductivity in an aluminum element.

Earlier, in a number of works, modeling the bubbles formed underneath the anode in the aluminum cell was performed. For example, the calculation of the effect of the large anode bubbles on the current distribution in the electrolyte and the liquid metal was carried out in [1]. The authors solved an equation of the electric current conservation using a three-dimensional model created in Ansys Mechanical APDL. The shape and dimensions of the bubbles generated under the anode were assumed to be known and were specified during the mesh construction. Another model of the bubbles motion is presented in article [2]. It takes into account movement of the individual bubbles, as well as a changing bubble’s shape during the process, and a coalescence. However, this model is computational expensive and, for this reason, is not suitable for use in the modeling of processes in the industrial cell. In [3], a model similar to [1] was applied in order to revise the equation, which determines the voltage...
drop across the bubble layer. A large number of papers are devoted to the simulation of the magnetic hydrodynamics in the industrial cells [4-9]. However, the combined influence of the magnetic forces, as well as the formation and motion of the anode bubbles on the electrolyte and metal movement, and the formation of the metal-electrolyte interface have not been previously evaluated.

In the present work a three-dimensional numerical model has been proposed that allows us to evaluate the electrolyte and metal flows under the influence of the magnetic forces, and also due to the motion of the gas formed underneath the anode. Also, it will be possible to determine more accurately the metal-electrolyte interface and estimate the MHD stability of the cell.

2. Description of the model

2.1. Physical Domain

The geometry of an industrial cell with a cross section in the plane of symmetry is shown in figure 1. The model includes three anodes, anode holder, anode and cathode busbar, potlining and cathodic steel shroud. The total length of the cell is 268 cm, width is 188.8 cm. The anode width is 48 cm, the central anode width is 43 cm. The anode length is 70 cm, the height is 40 cm. The gap between the anodes is 3 cm. The initial level of the metal and electrolyte is 22 and 23 cm, respectively. The anode-cathode distance is 5 cm.

![Figure 1. Geometry of the computational area: 1 - cathode aluminum busbar, 2 - cathode shroud, 3 - carbon sidewall, 4 - anodes, 5 - anode holder, 6 - anodic aluminum busbar, 7 - anodic aluminum rod, 8 - electrolyte, 9 - liquid aluminum, 10 - cathode block, 11 - refractory material (chamotte), 12 - heat-insulating material (vermiculite).](image)

2.2. Governing equations

For modeling movement of the metal, electrolyte and anode gas, a homogeneous model is used, according to which all three phases have the same fields of velocity, temperature and turbulence [10]. The change of the phase composition is simulated by the introduction of additional variables $r_\alpha$ is the specific volumes of each phase at a given point. When simulating the processes occurring in an electrolytic cell, all three phases are considered as the incompressible Newtonian liquids. The system of the hydrodynamics equations in the framework of a homogeneous model can be written in the following form:

\[
\frac{\partial}{\partial t}(\rho_r a) + \nabla(\rho ur) = S_a (\alpha = 1,3)
\]

the continuity equation of the phase $\alpha$ [11]:

\[
\frac{\partial}{\partial t}(\rho_r a) + \nabla(\rho ur) = S_a (\alpha = 1,3)
\]
\[
\frac{\partial}{\partial t} (\rho) + \nabla (\rho u) = 0,
\]

the Navier-Stokes equation with turbulence in the Reynolds approximation

\[
\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} (\rho u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] - \frac{\partial}{\partial x_j} \left( \rho u_i \bar{u}_j \right) + F_{e} + F_{b},
\]

where \( u \) is the average velocity of the mixture; \( u' \) is the pulsating velocity; \( k \) is the turbulent kinetic energy; \( \mu, \mu_t \) is the coefficients of the dynamic and turbulent viscosities, respectively; \( \delta_{ij} \) is the Kronecker symbol; the Lorentz electromagnetic force is determined by the expression \( F_e = J \times \vec{B} \); \( \vec{J} \) is the current density; \( \vec{B} \) is the magnetic induction; the buoyancy is determined by the volume force \( F_b = (\rho - \rho_{ref}) g \); \( \rho_{ref} \) is the reference density; \( p \) is the static pressure; \( \rho \) is the mixture density, \( g \) is the gravitational acceleration.

The parameters of the three-phase mixture in the equations (1)-(3) are determined by the formulas [11]:

\[
\rho = \sum_{a=1}^{3} r_a \rho_a, \quad \mu = \sum_{a=1}^{3} r_a \mu_a, \quad \bar{u} = \frac{1}{\rho} \sum_{a=1}^{3} r_a \rho_a \bar{u}_a.
\]

The heat transfer in the molten phase is determined by the solution of the energy equation:

\[
\frac{\partial}{\partial t} \sum_{a=1}^{3} \left( r_a \rho_a h_a \right) + \frac{\partial}{\partial x_j} \sum_{a=1}^{3} \left( r_a \rho_a \bar{u}_a h_a \right) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \lambda_{eff} \frac{\partial T}{\partial x_j} \right) + Q_J,
\]

\[
Q_J = \frac{J^2}{\sigma},
\]

\[
\lambda_{eff} = \sum_{a=1}^{3} r_a (\lambda_a + \lambda_t),
\]

where \( h \) is the enthalpy; \( \sigma \) is the electrical conductivity; \( \lambda_{eff} \) is the effective thermal conductivity, \( \lambda_a \) is the thermal conductivity of phase \( a \). In the energy equation, the term \( Q_J \) is responsible for the heat release in the control volumes of the model caused by the flow of electric current. The coefficient of thermal conductivity of solid materials is a function of temperature. \( \lambda_t \) is the turbulent thermal conductivity:

\[
\lambda_t = \frac{c_p \mu_t}{\text{Pr}_t},
\]

where \( \text{Pr}_t \) is the turbulent Prandtl number, \( c_p \) is isobaric heat capacity.

For calculate turbulence we used Shear-Stress Transport (SST) turbulence model k-\( \omega \) [11]. Maxwell equations system was solved to calculate magnetic forces.
2.3. Boundary conditions
An effective coefficient of the heat transfer was specified in order to work out the heat problem on the external surfaces in contact with air. The calculations were carried out for an ambient temperature of 0 °C. For the electrical problem, it was assumed that an electric current to the anode busbar was equal to 9 kA and the electric potential at the cathode busbar was zero. A zero normal component of the current density was specified for all external surfaces of the model. To identify the magnetic field at the boundary exceeding the dimensions of three electrolysis cells, the normal component of the magnetic induction was assumed to be zero. In order to solve the hydrodynamics problem on the inner surfaces of the lining contacting the metal and the electrolyte, the conditions for the normal and tangential components of velocity are set equal to zero. The anode gas evolution on the anode surface in contact with the electrolyte was considered. The carbon dioxide production is proportional to the normal component of the current density at the anode surface. A Fortran program was composed in order to define the mass production on the anode surface. During calculation this program determined the value of the normal component of the current density at the anode-electrolyte interface at each iteration, and then it established the appropriate distribution of the carbon dioxide mass consumption over the surface. A nullification of the gas phase was set on the upper surface of the electrolyte contacting the crust.

3. Numerical implementation
The numerical solution of the equations was carried out in commercial software packages ANSYS CFX 18.2, designed for computational fluid dynamics and ANSYS Maxwell, designed for calculations of magnetic fields. In addition to standard modeling tools, FORTRAN user subroutines were written to take into account the rate of gas evolution at the anode surface. The grid used for the solution consisted of 1662226 control volumes of hexahedral shape and 1907232 nodes. The area, where the hydrodynamic calculation was carried out consisted of 1136112 nodes and 1076504 elements. The calculation was carried out on a computer cluster using 60 cores. The exit to the stationary solution took about 10000 iterations, which required about a week of calculation.

4. Results and discussions
The temperature of the electrolyte and metal was in the range of 1216.5...1230 K. The cell temperature was set in such a way that the temperature of the electrolyte and the liquid aluminum did not fall below the liquidus of 1213 K. The electric and magnetic fields obtained as a result of calculation are given in figures 2, 3. The voltage drop in the cell was approximately 2.32 V, while the voltage drop due to the anode overvoltage was not taken into account. The cathodic overvoltage was not considered, either.

![Figure 2. Distribution of electrical potential in the cell, V.](image)

It can be seen from figure 3, that the values and type of the magnetic induction distribution correspond to the industrial cells operating at a current of 300 kA. Such a result was obtained as follows. First, the calculation of the magnetic fields on the current of 9 kA was performed, then the calculated magnetic induction fields were scaled to the experimental values, which were obtained in a cell of RUSAL (309 kA) using magnetometer MAL-3.2 [12]. Thus, the electromagnetic forces in the model were of the same order as in the industrial cell.
The current density at the anode bottom (top view) is given in figure 4. The current density at the anode center is less than at the edges. This fact can be explained by the greater thickness of the bubble layer in the center, which creates a large resistance, as well as an increased electric field at the sharp edges of the anode.

As can be seen in figure 5 the velocity in the electrolyte reaches a maximum value of 47 cm/s due to the lifting force of the bubbles. Figure 6 demonstrates the metal-electrolyte interface. Apparently,
the metal-electrolyte interface rises from the initial level in the space of the sidewall-anode by 0.018 m and descends by 0.015 m.

The influence of the electrolyte flow generated due to the anode gas movement on the electrolyte velocity field is clearly visible. In the space between the anodes, two vertical vortices are formed, the length of which almost coincides with the anode height. In the space between the anode and the sidewall, a rotational motion of the electrolyte is arisen. Near the anode, the velocity is directed upward, and in the vicinity of the sidewall the velocity, with values do not exceed 15 cm/s, is directed downward.

5. Conclusion
A new three-dimensional numerical model for evaluation of the magneto-hydrodynamic in the aluminum cell, considering the gas formation underneath the anode, has been proposed. Simultaneous account in the calculations of the movement bubbles and magnetic forces allows more accurately to determine the velocity field and the interface between the metal and electrolyte. The developed model can be used for design of new or modernization of existing aluminum reduction cells with novel anodes.

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