Numerical Simulation of Electromagnetic Stirrer Modernized by Using a Magnetodielectric Composite

K.E. Bolotin, I.A. Smolyanov, E.L. Shvidkiy, V.E. Frizen, S.A. Bychkov

Abstract

This paper presents the results of a study of the possibility of using a cermet composite based on Fe-Al2O3, as magnetodielectric inserts to increase the working gap between the inductor and the melt in the bottom electromagnetic stirrer with a rotating magnetic field. A three-dimensional model of a modernized laboratory facility for composite with a mass fraction of iron of 70% was studied. The model used previously measured electrical, thermal and magnetic physical parameters of composites. Numerical modeling of the problems of heat distribution in the modernized lining and the coupled electromagnetic-hydrodynamic-thermal problem of the temperature distribution in stirring molten metal was carried. A comparison of the results obtained for the standard and modernized stirrers has shown that the use of inserts is permissible in a limited range of values of the working gap.

Introduction

In terms of production and consumption, aluminum ranks first among the sub-sectors of non-ferrous metallurgy, and among the branches of metallurgy in terms of volume is second, cede only to steel production. The main consumers of aluminum are: aviation, space, automotive, construction and electrical industries, as well as a number of other areas [1].

Given importance, induction MHD technologies have long been used to intensify the metallurgical process for the production of aluminum [2]. However, the constant increase in the requirements for quality and cost of production leads to the need to modernize existing units.

One of the directions of modernization is the reduction of the value of the non-magnetic working gap directly affecting the efficiency of induction MHD installations. Its equal to the thickness of the lining, the large value of which is due to the chemical activity of the molten aluminum and the considerable temperature of the metal T≈700°C.

An analysis of the literature shows that over the past decades, many proposals have been made to solve this problem [3,4,5]. Separately, it is worth highlighting those in which there is a direct effect on the value of the non-magnetic working gap. For example, by introducing a special socket in the thickness of the lining to accommodate the inductor [6]. Another way is to reject the magnetic core, for more efficient cooling of the windings, drewed nearer as close as possible to the molten metal [7].

Despite the fact that these methods improve efficiency, they also have a number of weaknesses. Their use leads to an increase in the thermal load on the installation and an increase in the probability of an accident due to a reduction in the thickness of the liner. In this regard, new modernization options are needed, excluding these weaknesses.

A method has been proposed, comprising to install inserts in the lining, consisting of a composite material having magnetic, dielectric and high temperature properties. Such a solution will preserve the thickness of the lining, reduce the non-magnetic gap and exclude the
increase of the thermal load on the induction unit [8]. This article is devoted to a numerical study of the effectiveness of this method.

1. Samples of the inserts and their physical parameters

As a material for the inserts, cermet based on carbonyl iron and aluminum oxide (Fe-Al₂O₃) was chosen, two compositions containing 50% and 70% iron were investigated. The samples were pressed at a pressure P = 250 kg/cm² and burned at a temperature of T = 950°C. To measure the magnetic properties, the ammeter-voltmeter method was used for ring samples with a diameter of 70 mm. The electrical properties were measured by a two-contact method of impedance spectroscopy on tablets with a diameter of 10 mm. Thermal properties were obtained by laser flash and drop calorimetry methods. The results are shown in Table 1. Based on the results, it was decided to study the composition with 70% of iron.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>50/50</th>
<th>70/30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical Conductivity</td>
<td>8*10⁻⁴</td>
<td>3*10⁻³</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>3,3</td>
<td>9,6</td>
</tr>
<tr>
<td>Heat capacity</td>
<td>963</td>
<td>965</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>6,64</td>
<td>8,26</td>
</tr>
</tbody>
</table>

2. Model description

Figure 1 shows the three-dimensional geometry of the model of the modernized stirrer that was used in the study.

Fig. 1. Model of modernized stirrer (air hidden): 1 – molten metal, 2 – magnetodielectric inserts, 3 – inductor windings, 4 – magnetic core.

The geometrical and physical parameters of the model coincide with the parameters of the real-life laboratory stirrer and are shown in Table 2 [9]. The inserts are arranged so that there is always a distance of 10 mm between their upper side and the bottom of the molten metal.

In the course of the study, a multiphysical problem consisting of 3 parts was solved: electromagnetic, hydrodynamic and heat transfer in fluid.
Tab. 2. The geometrical and physical parameters of the model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of molten metal, mm</td>
<td>100</td>
<td>Length of model, mm</td>
<td>380</td>
</tr>
<tr>
<td>Length of molten metal, mm</td>
<td>90</td>
<td>Relative permeability of iron core</td>
<td>1200</td>
</tr>
<tr>
<td>Diameter of inductor, mm</td>
<td>100</td>
<td>Molten metal conductivity, S/m</td>
<td>5e6</td>
</tr>
<tr>
<td>Length of inductor tooth, mm</td>
<td>27</td>
<td>Molten metal density kg/m³ ρ(T)</td>
<td></td>
</tr>
<tr>
<td>Diameter of model, mm</td>
<td>445</td>
<td>Molten metal viscosity, Pa·s</td>
<td>0.002</td>
</tr>
</tbody>
</table>

2.1. Model description

The following refinements and assumptions were made in the model:
- the current frequency applied in stirrer is 50 Hz, so the magnetic field is quasistatic and the displacement current is ignored;
- the time variant electromagnetic force (EMF) is replaced by the time averaged EMF;
- the electrical conductivity of the molten metal does not depend on temperature;
- losses in the magnetic core and inserts are taken into account.

In the electromagnetic part, the Lorentz force was calculated, which is transferred to the hydrodynamic part.

2.2 Hydrodynamic part

Table 2 shows the calculation of basic criteria to determine the type and parameters of the hydrodynamic part. Based on the basic criteria and the conditions of the problem, the k-ω SST model of turbulence was chosen, and the following refinements and assumptions were introduced:
- calculation is carried out only in the molten metal region;
- free convective flows were not taken into account;
- the electromagnetic field of metal rotation does not affect the electromagnetic field of the inductor;
- the effect of the free surface is not taken into account;
- the influence of gravity is taken into account;
- the temperature influences the melt density parameter.

Tab. 3. The parameters of the hydrodynamic part of the problem.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number</td>
<td>$2 \times 10^3$-$3 \times 10^3$</td>
<td>The presence of turbulent flows in the stirrer ($Re &gt;&gt; Re_{cr}$)</td>
</tr>
<tr>
<td>Reynolds number (mag.)</td>
<td>$10^4$</td>
<td>Magnetic field of the melt does not affect the field of the inductor ($Re_{m} &lt;&lt; 1$)</td>
</tr>
<tr>
<td>Hartmann number</td>
<td>$3 \times 10^2$</td>
<td>Electromagnetic forces significantly superior to viscous forces</td>
</tr>
</tbody>
</table>

2.3 Heat transfer in fluids part

The temperature gradient was set as the initial condition from 949 to 964 K. The temperature has a dependence on the coordinate of the z axis, which coincides in direction with the axis of the cylinder of the molten metal. In this case, in the horizontal plane, the temperature of each layer is uniform.

As in the case of the hydrodynamic, the calculation was made only in the region of molten metal. Therefore, the boundary conditions are given in the form of thermal insulation for the bottom and side walls of the metal and the heat flux for the upper part. This heat flux corresponds to the contact of the metal with air. The radiation was not taken into account.
Also, in the course of the study, a second model was developed, which makes it possible to study the effect of insertion of the inserts on the temperature distribution in the lining. Its three-dimensional geometry is shown in Figure 2. This model includes only one part of the "Heat transfer in solids".

The model does not take into account the effect of temperature on its physical parameters, the temperature of liquid aluminum at the upper boundary (T = 973 K) and the room temperature at the lower boundary (T = 293 K) are set as boundary conditions. The lateral boundaries are temperature insulators. The heat released in the inserts as a result of the influence of the electromagnetic field on them is not taken into account, since it is negligible.

Evaluation of all processes in the stirrer was made by means of computer simulation in program COMSOL Multiphysics.

3. Mesh parameters

Since different types of problems have different requirements to the size of the mesh elements, two types were built, the first for the electromagnetic problem, the second for the hydrodynamic and heat transfer.

For the first mesh, the size of the finite elements in the melt was determined based on the depth of current penetration at 50Hz, the number of elements in the melt of 250,000, the total number of elements 540,000.

In Figure 3 the second mesh is shown, it was built only in the melt in order to save computing power, the size of elements was determined based on the values of the boundary layer Hartmann and equal to δ = 1 mm, the total number of elements was 440,000.
4. Results of numerical simulation

The results of calculating the electromagnetic force in the volume of molten metal for a standard and modernized unit with a working gap of 30 mm are shown in Figure 4. Two maxima corresponding to the two poles of the inductor are clearly visible.

Since calculations have been made for two types of units (standard and modernized) having different sizes of the working gap, it is necessary to introduce a criterion that will adequately assess the efficiency of various designs. As such a criterion, the time was selected for which a complete equalization of the temperature gradient in the volume of the molten metal occurs. Figure 6 presents a graph of the results of calculating the multiphysical problem for both types of installations with working gaps of 10 to 50 mm.

As a criterion for the second model, the temperature at the upper part of the tine of the magnetic core in contact with the lining or magneto-dielectric insert was chosen. The results of this calculation are shown in Figure 6. It follows from them that the introduction of inserts does not have a significant effect on the magnitude of the thermal effect on the installation.
Conclusions

The cermet based on Fe (70%)-Al2O3 (30%) can be used to modernized induction stirrer, to increase the value of working gap in 3-4 times, while the thermal effect decreases by more than 1,1 times. Despite the positive result, the loss of efficiency of the installation exceeds 30%. Therefore, it is necessary to carry out further work to improve the magnetic parameters of the cermet.

References


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