Modelling Vortex Fields in Metal Smelting Furnaces

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ABSTRACT
The present work is devoted to studying of electrovortical movements of the liquid metal in electric furnaces. The statement of a problem, physical and mathematical model of proceeding processes are given. The algorithm of the problem solution is developed and the result of electromagnetic fields in liquid metal executed by programmatic-calculable complex ANSYS is received.

Keywords: Lorentz force, modelling, electrovortex movement

1. INTRODUCTION

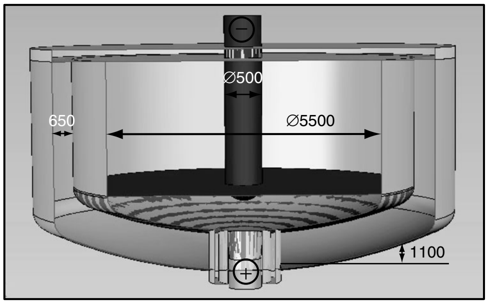
Direct-current electric furnaces with a bottom electrode have recently become very popular in metallurgy [1–3]. Such furnaces are more profitable and environmentally friendly. Typical circuit for such a furnace and its principle parameters are given in Fig. 1 [2]. The principle elements of the furnace are: a body with the lining backing, a smelting bath, top and bottom electrodes.

The furnace operation showed the increased wear at the bottom electrode. The reason for increased wear is supposed to lie in vortex currents of liquid metal caused by the Lorenz force [4]. Vortex current of liquid metal comes up because of spatial homogeneity of current density and electric-magnetic field. Therefore, the most important objective is to estimate the Lorenz force intensity, the affect of different factors on the Lorenz force and the vortex movement character of the molten metal.

Smelting metal in electric furnaces represents an extremely complex, energy consuming and expensive physical process that flows at high temperature, is accompanied by powerful electric and magnetic fields, intensive liquid metal vortex movements. These conditions make theoretical and experimental research much more complicated. That is why modern numerical methods and physical models of electric steel-smelting furnaces for numerical modelling have been widely used in metallurgy. Fundamental laws lying in the basis of the calculations make it possible to determine the strategic line of improving the technology no matter what occasional factors can come up in the real production process. Calculation of the processes in electric furnaces requires taking into account electromagnetic, thermal, strength and hydrodynamic phenomena and poses great demands to the means of numeric modelling.

2. PHYSICAL PROCESSES IN ELECTRIC FURNACES FOR SMELTING METAL

To describe physical processes in the furnace let us have a look at the electric direct-current steel-smelting furnace with symmetrical electrodes and axisymmetric bath, which is filled with liquid metal and is working in the steady-state mode. In Fig. 2 the typical configuration of the DC steel-smelting furnace with the axisymmetric bottom electrode is given. The main parts of the configuration are 1- fettle, 2-liquid metal, 3-top and bottom electrodes.



Furnace capacity m – 100 т
Diameter of furnaces D – 5500 мм
Depth of bath h with melted steel – 1100 мм
Direct current
Current load I – 80 – 100 кА
The mainlines voltage is U – 500 – 1000 В
Power of current consumption N – 40 – 100 МВт
Polarity – «+» on bottom electrode
Electrode diameter d – 500 мм
Lining thickness Δh_f – 650 мм
Specific conductance of lining σ_f – 2 $(\Omega{\cdot}\text{м})^{-1}$
Specific conductance of liquid metal σ – 0, 9 10^6 $(\Omega{\cdot}\text{м})^{-1}$.

Figure 1 Industrial DC arc furnace with bottom electrode.

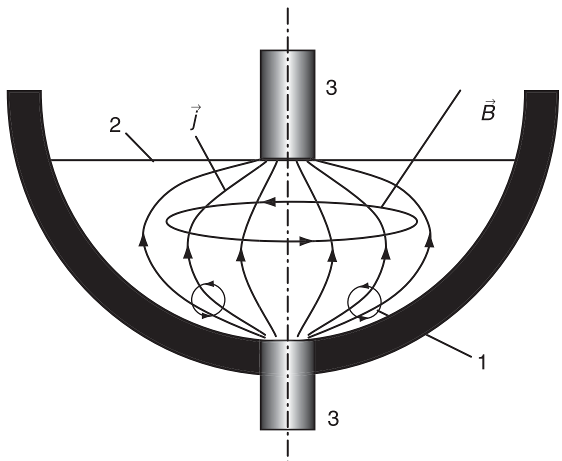


Figure 2 Model of physics process in DC arc furnace.

The DC potential is applied to the electrodes, positive voltage – to the bottom electrode, and negative – to the top one. Under the impact of the voltage given to the electrodes, the current is found in the molten metal. The current lines marked with symbol $\vec{j}$ in Fig. 2 lie in axial sections. From the Ampere's circuital law for any cross section of the furnace $I = \int_S \vec{j} d\vec{S} = const$, if S is the cross section area of the hearth of the furnace at a certain level, and current line path, it follows that the further it is from the symmetry axis the lower current density is.

This current generates axisymmetric magnetic field with magnetic inductive vector lying in the plane perpendicular to the symmetry axis, i.e. in the horizontal plane. Magnetic paths (marked with the $\vec{B}$ symbol) are concentric circles, perpendicular to the symmetry axis.

The current conductor in the magnetic field is affected by the Ampere force with the volume density of $\vec{f}_e = \left[\vec{j}, \vec{B} \right]$. This force is perpendicular to the current density $\vec{j}$ and magnetic induction $\vec{B}$. For the scheme in question the $\vec{f}_e$ force is directed towards the symmetry axis and lies in the axial plane. It has two components: radial and axial. The radial component is directed towards the symmetry axis, while the axial one is directed at the opposite electrode. The radial component causes cross-compression of the conductor, so-called pinch-effect.

This force affects the singled out element of the liquid conductor with the linear or rolling motion. Under the influence of this force the element moves as a whole towards the symmetry axis and rotates in the direction of the symmetry axis. But the conductor being liquid, the vortex flow appears. The necessary condition for the vortex flow ($\mathrm{rot}\,\vec{v} \neq 0$) to appear is the vortex nature of the electromagnetic force $\vec{f}_e(\mathrm{rot}\,\vec{f}_e \neq 0)$. Such a type of the flow appears if the current is spatially uneven.

In this example the vortex flow of liquid metal is the result of spatial unevenness of the current with the absence of outer magnetic field. The current in the liquid creates a magnetic field of its own, which causes vortex movement of the liquid.

3. MATHEMATICAL STATEMENT OF THE PROBLEM

To build a mathematical model of the processes in electric steel smelting furnace let us take the following assumptions.

- the medium is considered non-magnetic;
- the medium is a good conductor and its permittivity can be ignored;
- convective current, caused by the medium movements compared to the current of conductance can be ignored;
- heat convection may be caused by the uneven Joule heating and is taken into account by the dependence of the medium density on the temperature and pressure by the given law $\rho = \rho(p, T)$;
- medium heating caused by viscosity (viscous dissipation of energy) can be ignored as compared to the Joule heating;
- chemical reactions are not taken into account.

The processes flowing in the electric furnace during metal smelting are not steady. However, they are rather slow and can be described in quasi steady or just steady formulation. For steady processes the system of equations of magnetic hydrodynamics, describing the movement of the molten metal in the furnace is as follows [4–5]:
momentum equation

$$(\vec{v}\nabla)\vec{v} = -\frac{1}{\rho}\nabla p + \nu\Delta\vec{v} + \vec{g} + \frac{1}{\rho}\left[\vec{j},\, \vec{B}\right] \tag{1}$$

heat transfer equation

$$\rho c(\vec{v}\,\nabla)T = \chi\Delta T + \frac{j^2}{\sigma}; \tag{2}$$

equation of continuity

$$\nabla(\rho\vec{v}) = 0; \tag{3}$$

Maxwell's equations

$$\nabla\vec{B} = 0;\ \left[\nabla,\, \vec{H}\right] = \vec{j};\ \left[\nabla,\, \vec{E}\right] = 0;\ \nabla\vec{D} = \rho_e; \tag{4}$$

coupling equation (constitutive equation and Ohm's law for fluid in motion)

$$\vec{D} = \varepsilon\varepsilon_0\vec{E},\ \ \vec{B} = \mu\mu_0\vec{H},\ \ \vec{j} = \sigma\left(\vec{E} + \left[\vec{v},\, \vec{B}\right]\right); \tag{5}$$

charge conservation law

$$\nabla\vec{j} = 0; \quad (6)$$

where: $\vec{v}$ – liquid velocity, ρ – density, p – pressure, g – acceleration of gravity, ν – coefficient of kinematical viscosity, $\vec{j}$ – current density, $\vec{B}$ – field density, T – absolute temperature, c – specific heat of media, χ – heat conduction coefficient, σ – specific conductance, ε_0 и μ_0 – electrical and magnetic constant, $\vec{E}$ – dielectric field intensity, ρ_e – volume density of electric charge. Following forces are considered in equation (1): $-\rho^{-1}\nabla p$ – pressure force, $\nu\Delta\vec{v}$ – force of viscous drag, $\vec{g}$ – gravitation, $\rho^{-1}\left[\vec{j}, \vec{B}\right]$ – Lorenz electromagnetic force.

The equations given below express conservation laws of energy at transition through an interface of medium:
for electric field

$$E_{n1} = E_{n2},\ D_{n1} - D_{n2} = \rho_e; \quad (7)$$

for magnetic field

$$B_{n1} = B_{n2},\ \vec{n}\times\vec{B} = \vec{n}\times\left(B_n\vec{n} + B_\tau\vec{\tau}\right) = B_\tau = 0; \quad (8)$$

for current density on boundary with insulated and normal cross-section of electrode

$$j_n = 0,\ j_n = j_0 = I/S. \quad (9)$$

On the lines of the area calculated artificial non-reflective boundary conditions [6].

4. METHODS OF SOLUTION

The problem in question has no analytical solution and therefore it was solved numerically. As a result of the analysis of the numerical methods of solution the method of finite elements [7] and ANSYS system [8] were chosen. The problem belongs to the class of conjugate and the strategy of solution consists of the following stages:

1st stage – solving electromagnetic fields;

2nd stage – solving electrovortex flows;

3rd stage – solving electrovortex flows with the account of heat exchange and convection.

Such order is accounted for by the requirements to consequent conjugant analysis in ANSYS system [8–9]. The main idea of this analysis consists in joining two spheres (disciplines) by imposing the results of the solution of each stage as the loads for the following stage of the analysis. The results of the electromagnetic problem are the values of the components on X, Y, Z axes, electromagnetic force and magnetic flow density, found in each nodal point of the calculated area. Using these stages results, it is possible to calculate the components of smelting motions (2nd stage) caused by electromagnetic impact. Moreover, the result of the 1st stage is the amount of heat per the unit of volume got in every nodal point. The value of this heat can be used as initial data for heat exchange problem solution (3rd stage), which is the distribution of flow velocity. After that the found values of the temperature in every nodal point, as well as liquid metal velocity are specified taking into account heat exchange, convection and conditions of heat change on the boundaries of the calculated area and, as a result of this, we can do the calculation of the hydrodynamic problem.

5. MODELLING PROCESSES IN ELECTRIC FURNACES

Now let us have a look at the test problem of calculating electric and magnetic fields for axisymmetric volumetric conductor in the form of a cylinder that maximally correspond to industrial furnace (Fig 3). The calculated area by axial symmetry of the problem makes half the real area. 1 and 2 are electrodes, 3 is for iron cylinder, 4 is for medium (air). The initial data are as follows: current load I = 80 κA, specific conductance of liquid metal $\sigma_1 = 0{,}9\ 10^6\ (\Omega\cdot\text{м})^{-1}$, specific conductance of electrode $\sigma_2 = 0{,}2\ 10^6\ (\Omega\cdot\text{м})^{-1}$, relative permeability of liquid metal and electrode $\mu = 1$, relative permeability of media $\mu = 1$, relative capacitive of media $\varepsilon = 1$.

The calculations were made at the following boundary conditions:

- the current density on the electrode ends is given, or values of the potentials, corresponding to the initial current density;
- the conditions of continuity of the standard component objects on the side surfaces of the electrodes and cylinder are given;
- the conditions of continuation of the fields and infinity conditions are given;
- on the symmetry axis of the calculated area the conditions of axial symmetry are given.

The calculations were done by using different analyses at different schemes. It was found out that the results of the calculations had been considerably influenced by the size of the calculation mesh and by finite results. The preliminary analysis showed it is optimal to divide them into elements, as well as to shape them in quadrangular form with four nodes.

The domain was split into elements unevenly: in the area of the bottom electrode, where large gradients of electromagnetic parameters, elements were densely located and were of small size. The other parts of the domain where gradients of the parameters are not that significant the elements were located not so densely and were of larger size.

The effect of the boundary conditions on the artificial boundaries of the domain on the parameters in the central zone was investigated. It was found out that the results of boundary conditions changes are not significant in comparison with non-reflecting boundary conditions, and makes up about 0.7%.

In Fig. 4 demonstrated the vector and outline fields of the Lorenz force near the bottom electrode (anode). The results of the calculations prove the fact that the Lorenz force in such furnaces is determining if electro vortex flow appear. The given results are well-correlated with the experimental data (increased fettle wear).

Similar calculations were done in the COMSOL system. The results of calculations in ANSYS were compared with the results of calculations in COMSOL. The coinciding results of calculations by different methods and packets (Fig. 4) prove reliability of the models, methods and significance of the results.

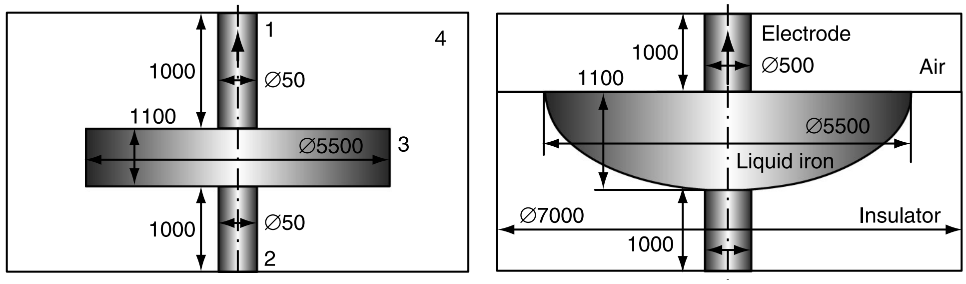


Figure 3 Model of industrial DC arc furnace.

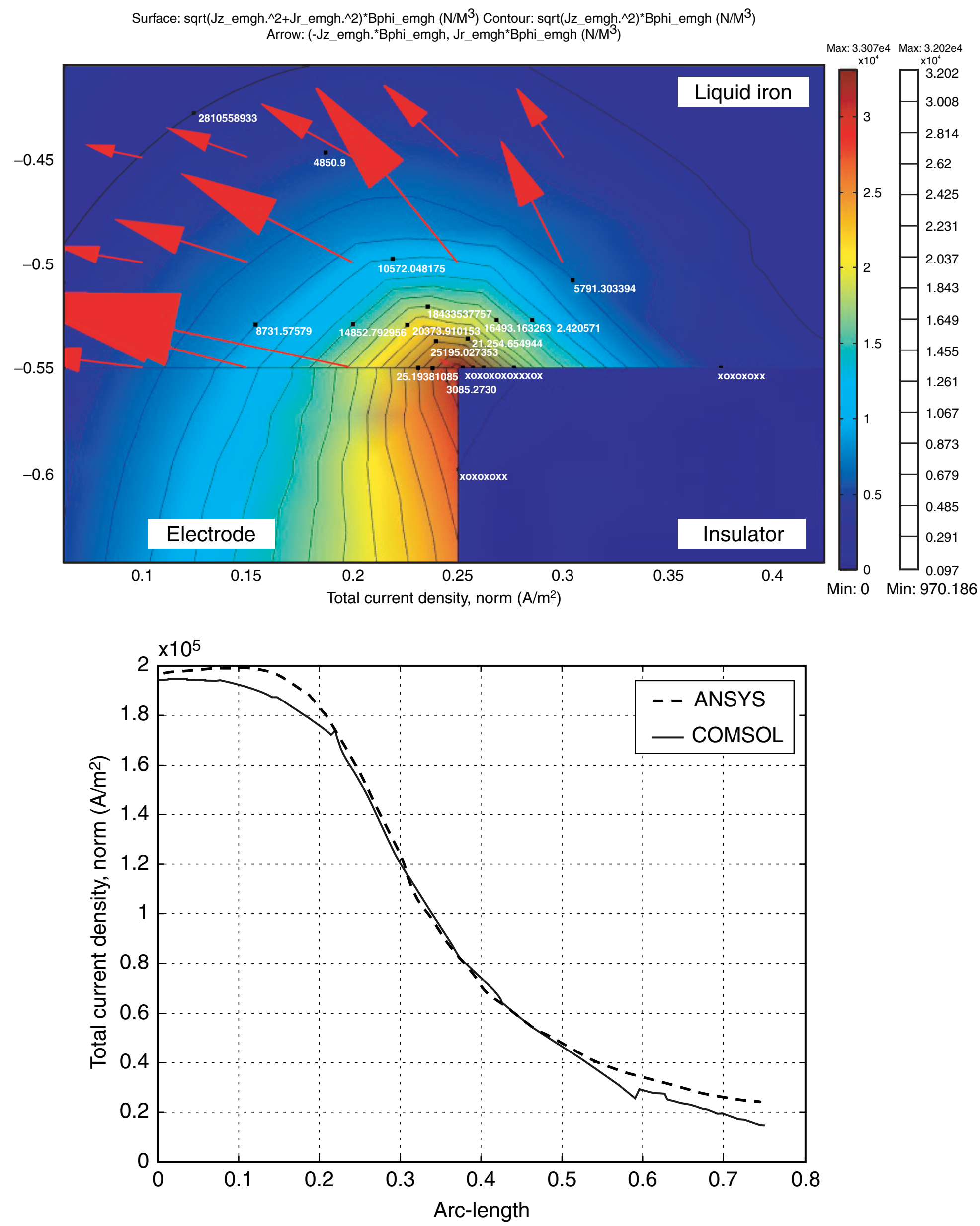


Figure 4 Vector and contour field of Lorenz force near the bottom electrode; Current density distribution j on distance 0,5 R from anode.

Next the axisymmetric model of the electric furnace was studied, whose form and size correspond to the industrial steel smelting furnace (Fig. 3). This model was worked out to study electromagnetic fields in the liquid steel. The intensity and character of the vortex electromagnetic forces in all the volume and near the bottom electrode.

Some results of the calculations for the industrial furnace model problem by using the calculation methods worked out on the previous model. Fig. 5 shows the fields of the current

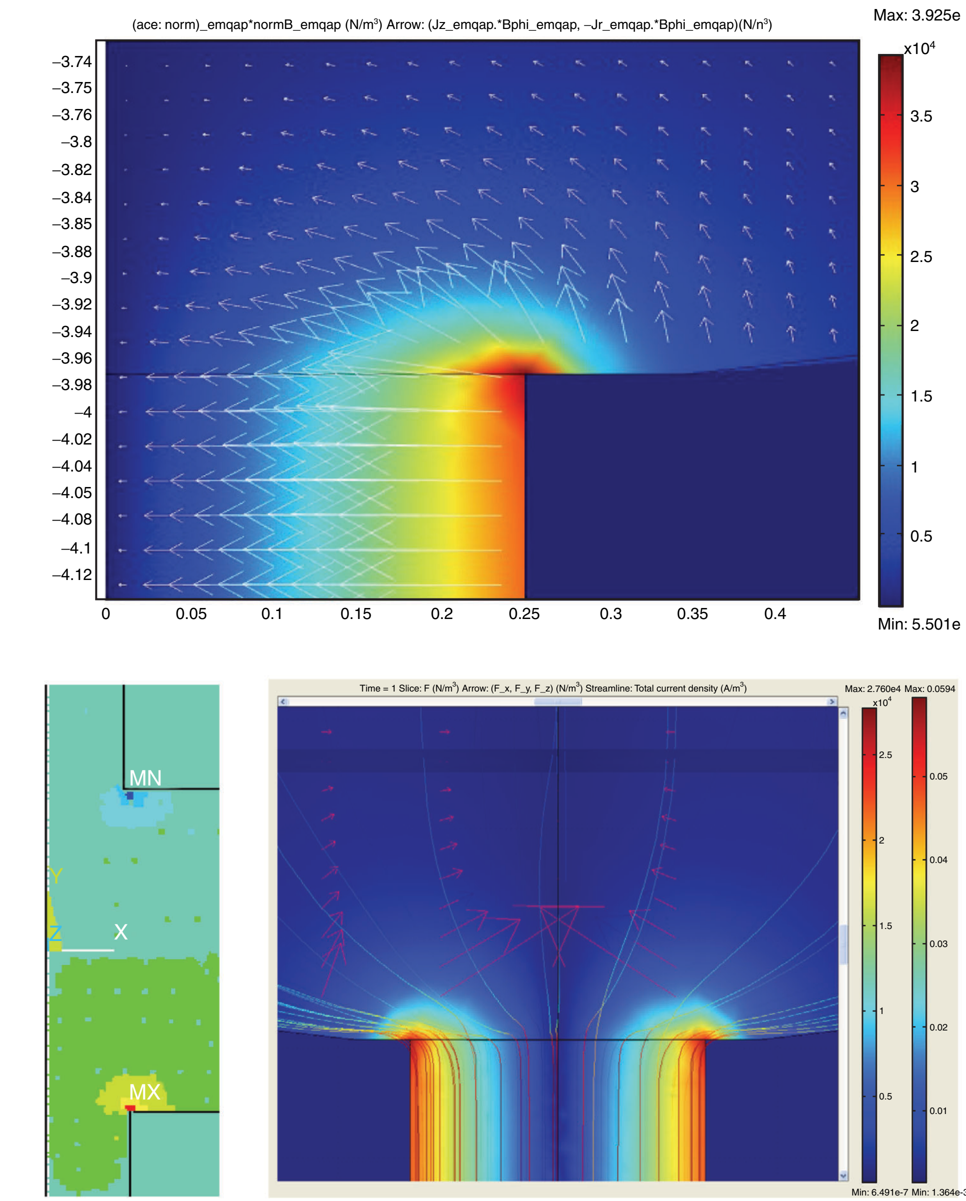


Figure 5 Field module of current density and Lorenz force vector near the bottom electrode and rotor Lorenz force; Field module and vector Lorenz force, current stream line near the bottom electrode. 3D formulation.

density for the model, the vectors of the Lorenz force in the area of the bottom electrode, as well as rotor (vortex) of the Lorenz force in the same area. These results allow to assess the forces intensity, causing the vortex motion near the anode.

The similar analysis for the model problem was carried out in 3D variant. In Fig. 5 you can see the results for different performances. You can see that the results take from axisymmetric 2D and spatial 3D performances are the same. However, the calculations for

3D are several times more time consuming. Therefore, it is reasonable to perform the analysis axisymmetrically.

The calculations let us come to the following conclusions. The suggested models and methods allow to calculate electromagnetic and force fields for the electric furnace model. It was stated that maximum value of the magnetic field induction, current density and the Lorenz force are located right near the anode (bottom electrode) at the distance of about the radius of the electrode. The farther from the anode, the lower are the values. According to the estimations, voluble density of the Lorenz force makes up about 30% of the gravity force.

6. CONCLUSIONS

The physical processes in the electric steel smelting furnace have been studied. It is proved that the spatial distribution of the current in the furnace leads to electro vortex motion of the liquid metal. To describe the processes in the electric furnace the model of the magnetic hydrodynamics is adopted. This model takes into account the spatial distribution of the current, electric and magnetic fields, temperature, the Lorenz force, the Joule heat and convection. The strategy of solving the stated conjugate problem is worked out, the methods of calculating electromagnetic fields in ANSYS have been worked on, the effect of the conditions boundary of the calculated area on the parameters of the central zone is assessed. The results of the calculations in ANSYS are compared with analytical assumptions, experimental data and calculations in COMSOL. Similarity of the calculations done by different methods proves the reliability of the methods and significance of the results.

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