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MODELLING VORTEX FIELDS IN METAL SMELTING FURNACES

MODELOWANIE ELEKTROWIROWYCH PÓL W PIECACH DO WYTAPIANIA METALI

Abstract

Work is devoted to study the electrovortical movements of the melted metal in electric furnaces. Description of a problem, physical and mathematical model of proceeding processes is resulted. The algorithm of the decision of a problem is developed and a result, of electromagnetic fields in melted metal, executed by programmatic-calculable complex ANSYS is received.

Keywords: Lorentz force, modelling, electrovortex movement

Streszczenie

W pracy przedstawiono modelowanie zjawisk zachodzących w piecach elektrycznych do wytopu metali. Wykorzystano system Ansys do analizy rozkładu pól elektromagnetycznych występujących podczas pracy pieca.

Słowa kluczowe: siły Lorentza, modelowanie, prądy elektrowirowe

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1. Introduction

Direct-current electric furnaces with a hearth 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, smelting bath, 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 (Ом·м)$^{-1}$
specific conductance of liquid metal
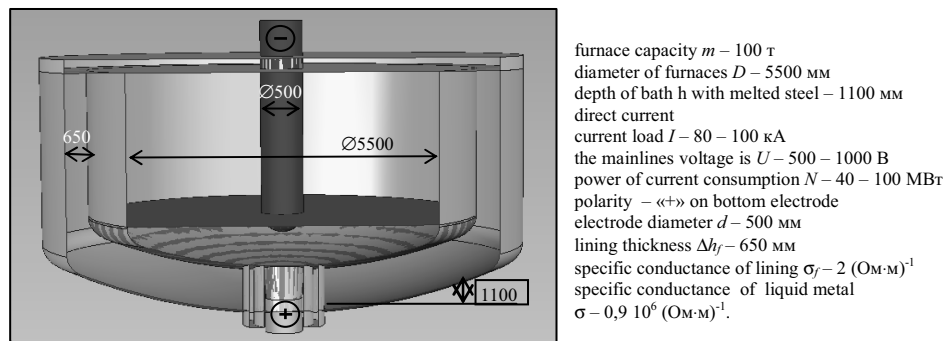σ – 0,9 10^6 (Ом·м)$^{-1}$.

Fig. 1. Industrial electrode-hearth arc furnace

Rys. 1. Schemat pieca przemysłowego

Operation of furnaces proved increased wear on the lining on the hearth electrode. The reason for increased wear is supposed to lie in vortex currents of molten metal caused by the Lorentz force [4]. Vortex current of molten metal comes up caused by spatial in homogeneity of current density and electric-magnetic field. Therefore a most important objective is to estimate intensity of the Lorentz force, affect of different factors on the Lorentz force and the character of the vortex movement of the molten metal.

Smelting metal in electric furnaces represents an extremely complex, energy consuming and expensive physical process, which flows at high temperature, is accompanied by powerful electric and magnetic fields, intensive vortex movements of the molten metal, which makes it much more difficult to do theoretical and practical research. It is the reason why it has become so popular to use modern numerical methods and physical models of furnaces for numerical modelling electric steel-smelting furnaces. Fundamental laws lying in the basis of the calculations, allow 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

Let us have a look at the hydrodynamic and electro-dynamic processes, going on in an electric direct-current steel-smelting furnace. Suppose, electrodes and furnace body are placed axisymmetrically, the metal got molten in the furnace, and direct current is given to

the electrodes, Positive voltage – the bottom electrode, negative – to the top one. For real furnaces the voltage on electrodes is U = 500–1000 V. Under the impact of the voltage given to the electrodes, current is found in the molten metal. Streamlines, marked with **j** symbol in Fig. 2 in meridional sections. From the Ampere's circuital law for any cross section of the furnace $I = \int_S \vec{j} d\vec{S} = \text{const}$, if S is the cross section area of the hearth of the furnace at a certain level, and streamline path, it follows that the further it is from the symmetry axis the lower must be the current density.
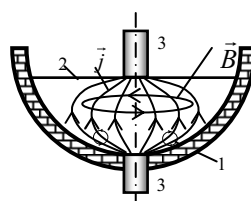

Fig. 2. Model of physics process in electrode-hearth arc furnace

Rys. 2. Schemat procesów fizycznych w elektrycznym piecu do wytapiania stali

This current makes axisymmetrical magnetic field, whose magnetic inducative vector will lie in the plane, perpendicular to the symmetry axis, i.e. in horizontal plane. Magnetic paths (they are marked with the **B** symbol) will be concentric circumference, 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 meridional plane. It has two components: radial and axial. The radial component is directed to 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 impacts the singled out element of the liquid conductor with the linear or rolling motion. Under the impact of this force the element will move as a whole towards the symmetry axis and rotate in the direction of the symmetry axis. But the conductor being liquid, the vortex flow appears. The necessary condition for the vortex flow ($\text{rot}\,\vec{v} \neq 0$) to appear is the vortex character of the electromagnetic force $\vec{f}_e$ ($\text{rot}\,\vec{f}_e \neq 0$). Such a character of the flow appears if current is spatially uneven.

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

3. Mathematical description of the problem

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

116

- 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 in to 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 quasisteady 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

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

heat transfer

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

equation of continuity

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

Maxwell's equations

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

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

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

charge conservation law

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

constitutive equation of continua in the next form

$$\rho = \rho(T) \qquad (7)$$

where:

$\vec{v}$	–	liquid velocity,
ρ	–	density,
P	–	pressure,
g	–	acceleration of gravity,
ν	–	coefficient of kinematic 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, $\rho^{-1}\left[\vec{j},\vec{B}\right]$ – Lorentz electromagnetic force.

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

$$E_{n1} = E_{n2}, \ D_{n1} - D_{n2} = \rho_e \tag{8}$$

for magnetic field

$$B_{n1} = B_{n2}, \ \vec{n} \times \vec{B} = \vec{n} \times \left(B_n\vec{n} + B_\tau\vec{\tau}\right) = B_\tau = 0 \tag{9}$$

for current density on boundary whith insulant and normal cross-section of electrode

$$j_n = 0, \ j_n = j_0 = I/S \tag{10}$$

On the lines of the area calculated artificial nonreflective boundary conditions [6].

4. Methods of solution

The problem 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 coupled and the strategy of solution consists of the following stages:

1st stage – modelling electromagnetic fields,
2nd stage – modelling electrovortex flows,

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

Such order is accounted for by the requirements to consequent coupled 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. On the base of these stages it is possible to calculate the components of smelting motions speed (2nd stage) caused by elecgromagnetic 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 on as initial data for heat problem solution (3rd stage), which solutions is distribution of flow speeds inside the melt. After that specifying the found values of the temperature in nodal point and melt speed without taking into account heat exchange and convection, and conditions of heat change on the walls of the calculated area we can do the calculation of the hydrodynamic problem.

5. Modelling processes in electric furnaces

Let us have a look at the test problem of calculating electric and magnetic fields for axisymmetrical volumetric conductor in the form of a cylinder close in size to a real 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: current load I = 80 кА, specific conductance of liquid metal $\sigma1 = 0,9\ 106$ (Ом·м)-1, specific conductance of electrode $\sigma2 = 0,2\ 106$ (Ом·м)-1, relative permeability of liquid metal and electrode $\mu = 1$, relative permeability of media $\mu = 1$, relative capacitivity of media $\varepsilon = 1$.
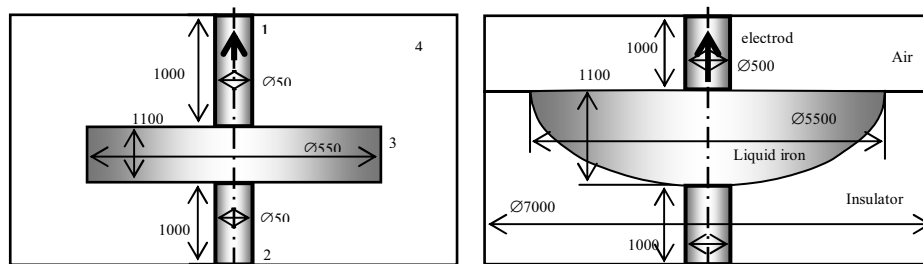

Fig. 3. Model of industrial electrode-hearth arc furnace

Rys. 3. Model pieca przemysłowego oraz pieca do wytapiania stali

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 were given.

The calculations were done by using different analyses at different schemes. It was found that considerable impact on the results of the calculations by the size of the calculation scheme and for of the 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 calculated area was split into elements unevenly: in the area of hearth electrode, where large gradients of electromagnetic parameters, mesh is finer. The rest parts of the calculated area, where gradients of the parameters are not that significant, the elements are located not so densely and are of larger size.

The impact of the boundary conditions on the artificial boundaries of the calculated area on the parameters in the central zone. It was found that the impact of boundary conditions changes are not significant in comparison with nonreflecting boundary conditions, and makes about 0.7%.

On Fig. 4 are vector and outline fields of the Lorentz force by the hearth electrode (anode). The results of the calculations prove the fact that the Lorentz force in such furnaces is determining if electrovortex flow appear. The given results are well-correlated with the experimental data (increased cladding wear).

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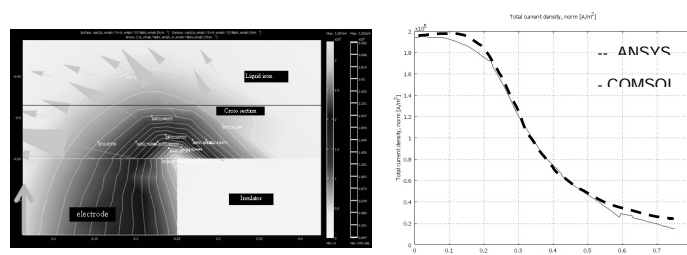

Fig. 4. Vector and contour field of Lorentz force near bottom electrode, disposal current density j radially cross section on distance 0.5 Rc from anode

Rys. 4. Pole wektorowe oraz pole konturowe siły Lorentza w okolicy anody, rozdział gęstości prądu j wzdłuż promienia w przekroju poprzecznym w odległości 0.5 Rc od anody

Next the axisymmetrical model of the electric furnace was studied, which form and size correspond to the real steel smelting furnace (Fig. 3). This model was for studying electromagnetic fields in the molten steel. The intensity and character of the vortex electromagnetic forces in all the volume and neat the hearth electrode.

Below are given some results of the calculations, taken for the model problem by using the calculation methods worked out on the previous model. In Fig. 5 the fiels of the current density model is depicted and the vectors of the Lorentz force in the area of the hearth electrode, as well as rotor (vortex) of the Lorentz force in the area of the electrodes which allows to assess the intensity of forces, causing the vortex motion near the anode.
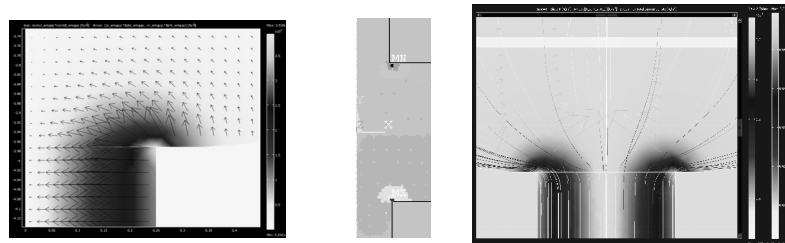
Fig. 5. Field module of current density and Lorentz force vector near bottom electrode and rotor Lorentz force, field module and vector Lorentz force, current streamlets near bottom electrode. 3D formulation

Rys. 5. Pole gęstości prądu oraz wektora siły Lorentza w okolicy dolnej elektrody, wektor siły Lorentza, linie prądu w okolicy dolnej elektrody

Similar analysis for the model problem was carried out in 3D variant. In Fig. 5 you can see the results for different models. You can see that the results are the same, both taked from axisymmetrical 2D and spatial 3D performances. However the calculations for 3D are several times more time consuming. Therefore it is reasonable to perform the analysis in axisymmetrical performance.

The calculations allow us to come to the following conclusions. The suggested models and methods allow to calculate electromagnetic and force fields for the model of the electric furnace. It was stated that maximum value of the magnetic field induction, current density and the Lorentz force are located near the anode (hearth 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 Lorentz force makes about 30% of the force of gravity.

6. Conclusions

The physical processes in the electric steel smelting furnace are studied. It is proved that the spatial distribution of the current in the furnace leads to electicovortex motion of the molten metal. To describe the processes in the electric furnace the model of the magnetic hydrodynamics is adopted, it takes into account the spatial distribution of the current, electric and magnetic fields, temperature, the Lorentz force, the Joule heat and convection. The strategy of solving the stated coupled problem is worked out, the methods of calculating electromagnetic fields in ANSYS are worked on it, the impact of the conditions on the boundaries 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 speaks about the reliability of the methods and significance of the results.

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