SOME METHODS FOR ELECTROVORTEX FLOWS CONTROL IN DC ARC FURNACES WITH BOTTOM ELECTRODE

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Abstract: The paper is devoted to simulation of vortex flows in the DC electric arc furnaces with different temperature and positions of the bottom electrode. The electromagnetic, temperature and hydrodynamic distribution parameters are obtained. The shear stress on the fettle area is offered as a criterion for the estimation of vortex flows influence on the increased wearing of the fettle. It is shown that the bottom electrode lifting above the surface at the electrode radius leads to the decrease of shear stress on the fettle area by 30% and cooling down the bottom electrode to the melting metal temperature – by 15%.

1. Introduction

The DC electric arc furnaces (EAFs) with the bottom electrode in the industrial practice has shown higher efficiency, low heat loss, lower components wear and higher quality of steel produced [1]. The exploitation of these furnaces has shown a high rate of fettle wear near the bottom electrode that connected with electrovortex flow [2]. Electrically vortical flows (EVF), appearing under electromagnetic forces as a result of non-homogeneous distribution of the current density through the liquid conductor, can be observed in many technological processes: electro slag remelting process (including DC and AC EAFs, electrolysis cells and submerged-resistor induction furnaces), arc welding, processes of semiconductor crystals growing, electro vortex engines etc [3]. The present paper deals with the electrically vortical flows in numerous model tasks for DC EAFs with different parameters of bottom electrode.

2. Presentation of the problem

The operation period of DC EAFs with the bottom electrode can be divided into the following stages: melting of the burden; liquid period when steel is produced; tapping. The time of liquid period ranges from 15 % to 60 % of all operation period depending on the steel type that is produced and on the quality of starting raw material [1]. It is essential that the processes in DC EAFs during the liquid period should be estimated.

In this type of furnaces 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.

Convection flows make its own contribution to the vortex flow and appear under uneven distribution of the temperature throughout the liquid volume. It is shown in the work [3] that heat convection in electrovortex flow with axial symmetry appears when the radial gradient exists ($\partial T/\partial r \neq 0$). The direction of convection depends on increase or decrease of temperature value with the increase of the distance from the axis of symmetry.

To build the mathematical model of EVF the magneto hydrodynamic model is adopted with the following assumptions: the medium is considered non-magnetic and a good conductor, convective current can be neglected, physical characteristics of the medium are assumed to be homogeneous and isotropic and depend on temperature.

During the liquid period the temperature difference throughout the metal volume can range depending on the mode of furnace operation. Thus, when the arc works at full power the temperature ranges from 3773 K in the arc area at the cathode to 1923 K in the bottom electrode area and along the fettle surface. At the low power of the arc the temperature difference throughout the metal volume does not exceed 50 K. It should be noted that the metal at this period is liquid.

The velocity of the liquid that appears under electromagnetic force can be estimated as $u_0 = j_0 L\sqrt{\mu_0/\rho} \approx 0.3 m/s$ [3]. The Grashof number that defines the ratio of relative intensity of convection depending on the temperature range and electrovortex flow in the furnace is ranged in different periods from $Gr = 0.5 < 1$ (with the low power of the arc) to $Gr = \beta \Delta T g L / u_0{}^2 \approx 18.5 > 1$ (with the full power of the arc), that corresponds to the insignificant or essential contribution of the convection to the general vortex flow [3]. According to the preliminary estimation during the full arc power period it is necessary to take convection into account, but convection can be neglected at the period of low arc power.

The relative power of Joule heating as compared with another heat source (heat from the arc) is low $Q = \frac{j_0^2 L}{\sigma \rho c u_0 \Delta T} \approx 10^{-3} << 1$. This means the arc heat is more intense than joule heating [3]. Peclet heat number that defines the ratio of the free heat convection transfer to the molecule heat conduction equals $Pe = u_0 L/\chi \approx 10^{-5} << 1$ that means the domination of molecule heat conduction over free heat convection [3].

The magnetic Reynolds number is a part of the magnetic induction equation. The magnetic Reynolds number is low in this problem ($Re_m = \mu_0 \sigma u_0 L \approx 0.4 < 1$), meaning that the movement of liquid conductor does not change the magnetic field and the calculation can be carried out in non-induction approximation [3].

The processes in the DC EAFs during metal smelting are not steady. However, they are rather slow and can be described in quasisteady or just steady formulation. For steady statement the molten metal movement in the furnace can be described by the system of equations for magnetic, heat transfer and hydrodynamic processes.

The electromagnetic processes in liquid metal can be described by Maxwell's equations

$$\nabla \times \vec{B} = \mu_0 \vec{j}, \nabla \cdot \vec{B} = 0, \tag{1}$$

$$\nabla \times \vec{E} = 0, \ \nabla \cdot \vec{E} = \frac{\rho_e}{\varepsilon_0}, \tag{2}$$

Ohm's law for fluid in motion

$$\vec{j} = \sigma\left(\vec{E} + \vec{u} \times \vec{B}\right) \tag{3}$$

and charge conservation law

$$\nabla \cdot \vec{j} = 0, \tag{4}$$

where $\vec{j}$ – current density, ρ_e – charge density, $\vec{B}$ – magnetic induction intensity vector, $\vec{E}$ – electrical field intensity, σ – specific conductance, μ_0 – permeability of free apace, ε_0 – permittivity of free space, $\vec{u}$ – liquid velocity.

The heat parameters are calculated by heat transfer equation

$$\rho C_p u \cdot \nabla T = \nabla \cdot ((a + a_T)\nabla T) + j^2/\sigma, \tag{5}$$

where ρ – density, C_p – specific heat , T – temperature, a – heat conduction coefficient, a_T – turbulent heat conduction coefficient, j^2/σ – Joule heats source.

The hydrodynamic processes in the liquid can be described by Navier-Stokes equation

$$\rho\vec{u}\cdot\nabla\vec{u} = \nabla\cdot(-pI + (\eta+\eta_T)(\nabla\vec{u} + (\nabla\vec{u})^T) - (2/3)(\nabla\cdot\vec{u})I) + \rho\vec{g} + \vec{j}\times\vec{B}\,; \qquad (6)$$

and equation of continuity

$$\nabla\cdot(\rho\vec{u}) = 0\,, \qquad (7)$$

where p – pressure, $\vec{g}$ – gravitation, υ – dynamic-viscosity coefficient, $\eta = \upsilon/\rho$ – coefficient of kinematics viscosity, $\vec{I}$ – identity operator for points on the boundary. The following forces are considered in the equation (6): $-\nabla\cdot p$ – pressure force; $\nabla\cdot(\eta+\eta_T)(\nabla\vec{u} + (\nabla\vec{u})^T)$ – force of viscous friction; $\vec{j}\times\vec{B}$ – Lorentz electromagnetic force.

According to the preliminary estimation the Reynolds number under the movement in DC EAF is $Re = u_0 L/\nu \approx 10^6$, which is equivalent to the developed turbulent flow that can be described within $k-\varepsilon$ turbulence model.

To build a model of the processes in liquid metal the parameters of the industrial DC EAF with the bottom electrode are taken into account [4]. The geometrical arrangement of the furnace has been shown in Fig. 1

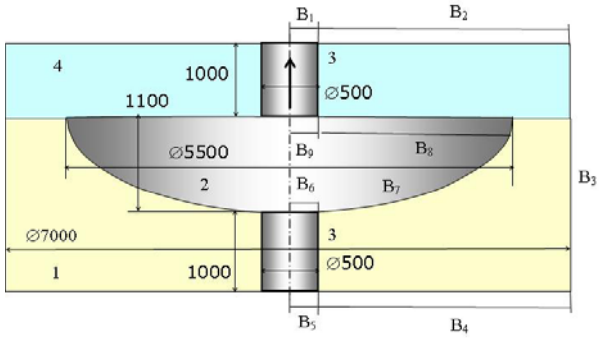
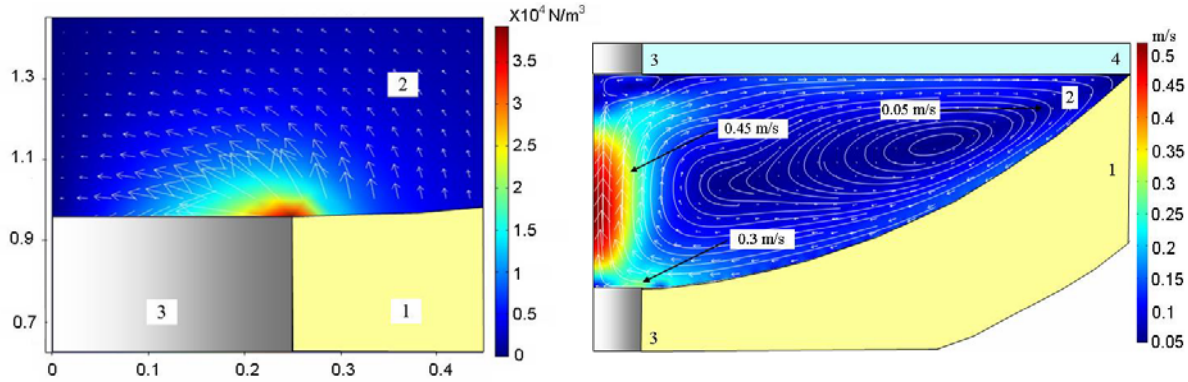


Figure 1: 1 The arrangement of cylindrical DC EAF
(1 – fettle, 2 – liquid metal, 3 – electrodes, 4 – slag).

The main parts of the configuration in Fig. 1 are 1 – fettle, 2 – liquid metal, 3 – top and bottom electrodes, 4 – slag. The axial symmetry allows calculating the half of the cross-section area. Its main parameters are: furnace capacity – 100 t, direct current load 80-100 kA, the mainlines voltage is 500-1000 V, power of current consumption 40-100 MW, polarity – «+» on bottom electrode.

The formulated problem was solved with the corresponding boundary conditions that are defined in fig. 3 as B_1-B_9. Electromagnetic conditions: B_1, B_5, B_6, B_9 current density on the boundary with normal cross-section of electrode $j_n = j_0 = I/S$, where S - cross section of electrode; B_8, B_7 current insulation j_n=0; B_6, B_7, B_8, B_9 the conditions of continuity of electric and magnetic fields $E_{\tau_1} = E_{\tau_2}$, $D_{n_1} = D_{n_2}$ and $B_{n_1} = B_{n_2}$, $B_{\tau_1} = B_{\tau_2}$. Heat conditions: B_9 – constant temperature of electric arc T_1 = 3300 K; B_6 – constant temperature on bottom electrode T_2 = 1980 K; B_8 – constant temperature on boundary with slag T_3 = 1900 K; B_7 – constant temperature on boundary with fettle T_3 = 1900 K. Hydrodynamic conditions: B_6, B_7, B_8, B_9 the no-slip boundary condition on all boundaries of liquid was used, both on the boundary of the liquid with the fettle and the boundary of liquid with slag. The last approximation is based on the fact that slag viscosity is much higher than liquid viscosity and it can be considered as no-slip condition.

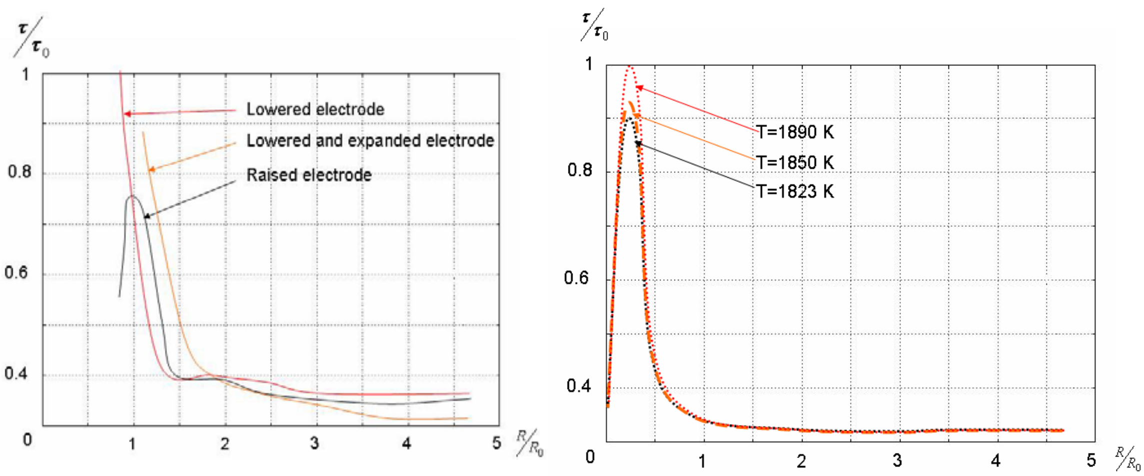
Some results of simulation the processes proceeding in liquid steel are given below. Fig. 2a demonstrates the vector and contour fields of the Lorentz force near the bottom electrode (anode) and Fig. 2b hydrodynamic fields of velocity vector, contour and streamlines, where 1 – fettle, 2 – liquid metal, 3 – bottom electrode. The value of Lorentz force ranged and comprised about 30 % of volumetric gravity force. The figure demonstrates that the higher intensity of vortex flows appears in liquid metal volume. The convection flows are in the line with electrovortex flows and vortex flows increases. The maximum value of the vortex flow velocity was located on the axis of symmetry and reaches 0.5 m/s. The vortex flow velocity value in close to the bottom electrode and the fettle comprises about 0.3 m/s



a) b)

Figure 2: a) the vector and contour field of Lorentz force near the bottom electrode; b) the vector, contour field and streamlines of velocity with convection.

The change of the bottom electrode position and temperature are two of the possible ways to reduce the negative influence of the liquid metal vortex flow on the increased fettle wearing. To estimate this effect some simulation of hydrodynamic processes at different positions and temperature of bottom electrode has been done.



a) b)

Figure 3: Comparison of the shear stress on fettle surface at different bottom position and temperatures on the distance to the axis of symmetry ($\tau_0 = 120$ Pa, $R_0 = 0.25$ m).

Fig. 3 are shown comparison graphs of the values of the shear stress as a function of distance from the axis of symmetry for different bottom electrode position and temperature. Graph shows the magnitude of the shear stress in dimensionless coordinates. As the scale of the shear stress is taken the characteristic value of this quantity for the standard electrode ($\tau_0 = 120$ Pa) on the distance, expressed in electrode radius ($R_0 = 0.25$ m).

It is shown that lifting the bottom electrode above the surface of the fettle by the electrode radius value leads to the decrease of the shear stress on the fettle area by 30 %, while putting the bottom electrode lower than the fettle surface by the electrode radius value and expending the bottom electrode to the electrode radius value reduce the stress by 10 % [5].

To reduce the negative impact of the melt vortex movement to the bottom electrode and fettle near it, a series of numerical experiments with different bottom electrode temperature are carry out. The decrease of temperature bottom electrode has little effect on the general character and speed of the melt, but significantly affects to the velocity of the melt near the bottom electrode. Thus, when the temperature of bottom electrode comes to the melting point the metal velocity at shear sublayer is reduced by 20 %, while the value of the shear stress – by 15 % [6].

To verify the obtained results all calculations were done in ANSYS and COMSOL. At every stage the obtained results were compared with the known theoretical and experimental data and calculations received with the help of other software packages. The coincidence of the calculations done by different methods with analytical assumptions and experimental data in terms of all EVF characteristics under different conditions and with different installations proves the reliability of the methods and significance of the results [5-6].

3. Conclusion

The magnetohydrodynamic model for modelling EVF in different technological installations was adopted in the work. The research is carried out by computer modelling methods and software packages.

The processes in numerous laboratory and industrial installations, such as a laboratory installation with hemispherical volume filled with eutectic liquid and a DC EAFs with the bottom electrode, were simulated numerically. The specific features and laws of EVFs occurrence and course in these installations are determined.

The new criteria for the estimation of EVFs influence on the increased wearing of the bottom electrode and the fettle near it are offered: a rotor of the Lorenz force and shear stress on the fettle area. These criteria allow estimating the influence of the moving liquid on the fettle area. The criteria adequacy is confirmed by the theoretical researches and the good correlation with a number of experimental data.

The work offers the ways of EVFs control in the DC arc furnace with the bottom electrode by changing the bottom electrode position and temperature decrease at the bottom electrode of the furnace bath in order to increase the stability of the fettle wearing near the bottom electrode.

It is shown that the bottom electrode lifting above the surface at the electrode radius leads to decrease of shear stress on the fettle area by 30 % and cooling down the bottom electrode to the melting metal temperature – by 15 %.

The technique of EVFs control in the DC arc furnace with the bottom electrode is developed, allowing to reduce the fettle wearing and to optimize the furnace work.

4. References

[1] Nekhamin, S.M., Lunin, A.G., Krutyanskii, M.M., Filippov, A.K.: DC arc melting furnaces. Refractories and Industrial Ceramics, vol. 46 (2005), no. 1, 37-39.

[2] Zaycev, V.A., Medovar, L.B.: Bottom electrodes of DC arc furnace, SEM, 2009, No 2, pp. 3-8 (in Russ.).

[3] Bojarevics, V., Freibergs, J., Shilova, E., Shcherbinin, E.V.: Electrically Induced Vortical Flows, Riga: Zinatne, 1985, 315 p. (in Russ.).

[4] Michielan, A, Lavaroni, G, Fior, A: The Danieli Danarc TM furnace, ABS Rev. Met., France, 2000, no. 6, pp 745-752.

[5] Kazak, O.: Modelling of vortex flows in DC electric arc furnace with different bottom electrode positions, Metallurgical and Materials Transactions B, vol. 44 (2013), no 5, p. 1243-1250.

[6] Kazak, O.: Numerical modelling of electrovortex and heat flows in DC electric arc furnace with cooling bottom electrode, Heat and Mass Transfer 2013, DOI: 10.1007/s00231-013-1265-1.