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Stirring of Liquid Steel in Crucible Induction Furnace

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Abstract

The paper deals with mathematical and computer modelling of nonisothermic electromagnetic stirring of steel in a ceramic crucible. The process is characterized by interaction of electromagnetic field, temperature field and field of flow. Another complication is caused by deformation of free level. The theoretical analysis is supplemented with an illustrative example solved numerically by combination of professional programs and procedures developed and written by the authors.

Introduction

Induction melting of cast iron or steel and their preheating in typical induction crucible furnaces belongs to important and commonly used industrial technologies. Quality of final products strongly depends on homogeneity of metal composition as well as on uniform temperature distribution within all the volume of melt.

The process is, however, typical by considerable consumption of electric energy. In order to reach high efficiency of the corresponding device that must, moreover, work reliably and effectively as much as possible, we need to know perfectly all physical phenomena accompanying its operation. And this is an uneasy business, still representing a challenge. The main reason is that these phenomena are characterized by interaction of several physical fields. The dominant one is always harmonic or periodical electromagnetic field producing temperature field and field of flow. All these fields may strongly influence one another, which significantly complicates the situation. The mathematical models of the process [1]–[3] are then usually given by a set of partial differential equations (often nonlinear and nonstationary) whose coefficients are functions of the state variables such as temperature and pressure (and other problems may occur in association with setting of the correct boundary conditions). And even when the model well describes the physical reality, the present knowledge and computational technology allow its solving only under various simplifications. Of course, research in the area of ever more perfect methods and algorithms for solving the above tasks is conducted at a number of universities and other scientific institutions all over the world, but anyway, there still remains much to do to describe the physical reality in its whole complexity.

The solution of the task starts from constitution of the basic mathematical model consisting of the Helmholtz elliptical partial differential equation for electromagnetic field, nonlinear Navier-Stokes equation for steady-state flow field and Fourier diffusion parabolic equation supplemented with velocity component for non-stationary temperature field. Meniscus of the free surface boundary is also taken into consideration. The final result of mathematical modelling is the evolution of temperature to the moment when its average value in molten steel reaches the requested value. The simulations are realized by means of the 3D professional FEM-based codes ANSYS supplemented by several codes prepared by the authors. The important point of the paper is represented by an illustrative example describing modelling of the process in a particular technological line for casting of iron rolls. The results are discussed in order to establish next research steps.

1. Continual mathematical model of the problem

Consider an arrangement depicted in Fig. 1. Molten steel is heated in a fire-clay crucible surrounded by the inductor and shielding cylinder. The inductor that is made of massive hollow copper conductor intensively cooled by water is supposed to carry harmonic current of given amplitude and frequency. Permeability of ferromagnetic shielding parts is considered constant.

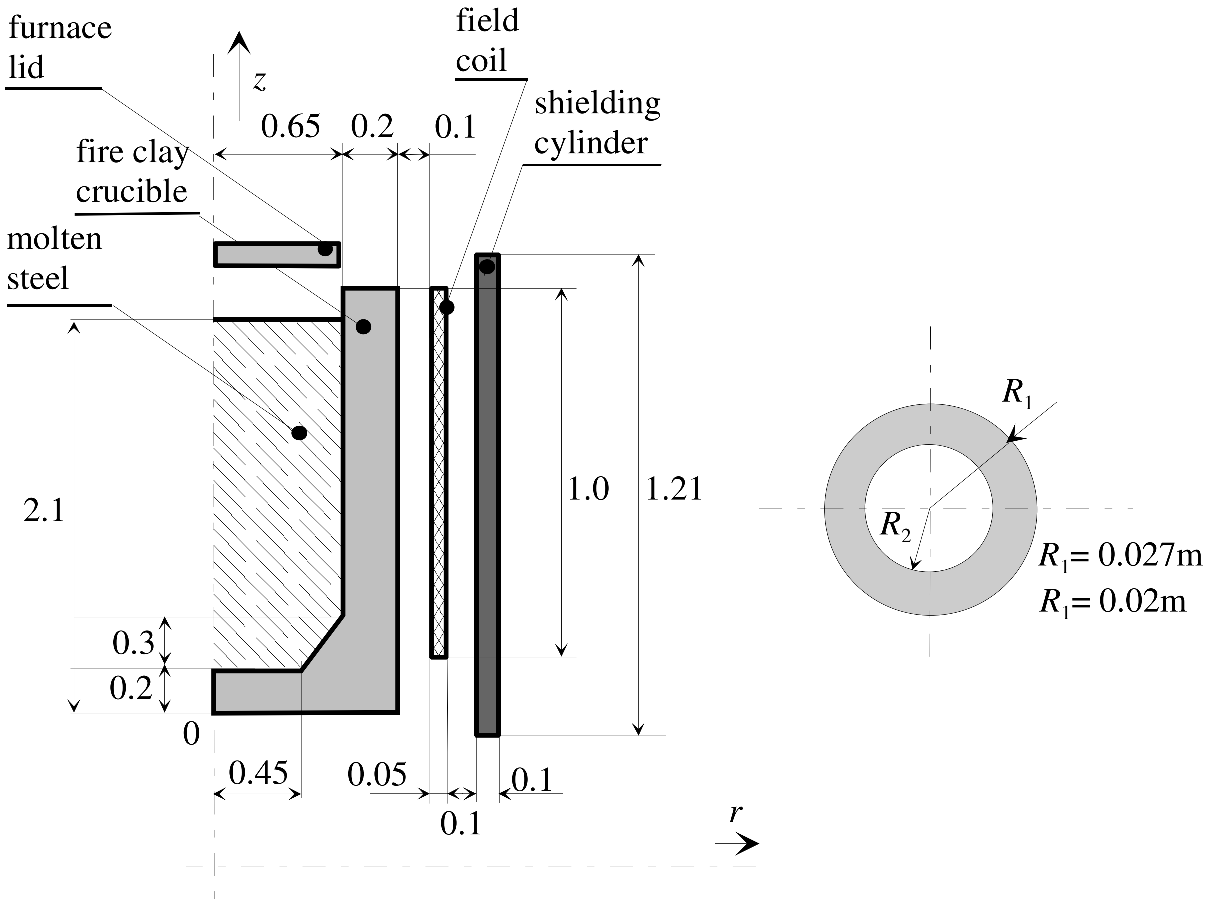

Fig. 1: The solved arrangement with principal dimensions and detail of the conductor

Electromagnetic field produced by periodical current has to be calculated in a larger region containing some neighborhood of the arrangement (as the shielding is often imperfect, the task has to be often treated as an open boundary problem). The governing equation providing distribution of the magnetic vector potential $\boldsymbol{A}$ reads [5]

$$\mathrm{curl}\left(\frac{1}{\mu}\cdot\mathrm{curl}\,\boldsymbol{A}\right)+\gamma\cdot\frac{\partial\boldsymbol{A}}{\partial t}=\boldsymbol{J}_{\mathrm{ext}} \tag{1}$$

where γ is the electrical conductivity, μ the magnetic permeability and $\underline{\boldsymbol{J}}_{\mathrm{ext}}$ the uniform current density delivered to the inductor from external source. Particular forms of this equation for individual subregions of the system can be obtained after putting there corresponding parameters γ, μ and $\underline{\boldsymbol{J}}_{\mathrm{ext}}$. The equation has to be supplemented with appropriate boundary conditions following from the solved arrangement. As long as we have to introduce an artificial boundary we used for this case the infinity elements offered by Ansys. As far as the system is linear, equation (1) may be simplified to the Helmholtz equation for the phasor of $\boldsymbol{A}$.

$$\mathrm{curl}\,\mathrm{curl}\,\underline{\boldsymbol{A}} + \mathrm{j}\cdot\mu_0\omega\gamma\underline{\boldsymbol{A}} = \mu_0\underline{\boldsymbol{J}}_{\mathrm{ext}}\,. \tag{2}$$

The second term $\gamma\cdot\dfrac{\partial \boldsymbol{A}}{\partial t}$ on the left-hand side of (1) represents the eddy current density $\boldsymbol{J}_{\mathrm{eddy}}$ generated in any electrically conductive part of the arrangement. Considering any point of the charge, the specific Joule losses and volume Lorentz force at this point may be calculated as

$$p_{\mathrm{J}} = \gamma\cdot\left(\frac{\partial \boldsymbol{A}}{\partial t}\right)^2, \tag{3}$$

$$\boldsymbol{f}_{\mathrm{L}} = \boldsymbol{J}_{\mathrm{eddy}}\times\boldsymbol{B} = \gamma\cdot\frac{\partial \boldsymbol{A}}{\partial t}\times\mathrm{curl}\,\boldsymbol{A}. \tag{4}$$

From the viewpoint of temperature, stirring may be either stationary or nonstationary process whose character is derived from further processing of molten metal. But anyway, as the system is characterized by thermal losses, the amount of the Joule heat produced in its electrically conductive parts must be at least equal to these losses. The general equation describing the distribution temperature in the system reads [5]

$$\mathrm{div}\left(\lambda\cdot\mathrm{grad}\,T\right) = \rho c\left(\frac{\partial T}{\partial t} + \boldsymbol{v}\cdot\mathrm{grad}\,T\right) - p_{\mathrm{J}}\,. \tag{5}$$

where λ denotes the thermal conductivity, ρ the specific mass of the heated material, c its specific heat and p_{J} is given by (3). The term $\rho c\boldsymbol{v}\cdot\mathrm{grad}\,T$ characterizes the heat transfer due to movement of liquid metal, whose velocity is $\boldsymbol{v}$.

The velocity field that is calculated in common with the pressure field only within molten metal is, in general, very difficult to obtain. As far as its Reynolds number is sufficiently low, it may be considered linear. Provided that the molten metal is incompressible, its behavior can be described by the Navier-Stokes equation [6]

$$\rho\cdot\left[\frac{\partial \boldsymbol{v}}{\partial t} + \left(\boldsymbol{v}\cdot\mathrm{grad}\right)\boldsymbol{v}\right] = -\mathrm{grad}\,p + \rho\boldsymbol{g} + \eta\cdot\Delta\boldsymbol{v} + \boldsymbol{f} \tag{6}$$

supplemented with the continuity equation

$$\mathrm{div}\,\boldsymbol{v} = 0. \tag{7}$$

Here $\boldsymbol{v}$ denotes the velocity (that is a function of position and time), p the pressure, η the dynamic viscosity and $\boldsymbol{f}_{\mathrm{L}}$ the internal volume Lorentz force given by (4).

In order to obtain the correct results, all equations (1), (5) and (6) have to be equipped with correct boundary conditions.

Free level of steel has a shape described by equation [1]

$$\frac{B^2}{2\mu_0} + \rho g h + \frac{\sigma}{R} = \mathrm{const} \tag{8}$$

where σ denotes the surface tension of melt, B the module of magnetic flux density, h the height of melt and R the radius of curvature. The value of const has to be determined from the total volume of melt.

2. Aspects of numerical solution

As the process of heating from the melting to the casting temperature takes tens of minutes, it was found that solution of the Navier-Stokes equation respecting temperaturedependent changes of material parameters within such a period is not possible (unacceptably long time of computations). Therefore, we solved somewhat simplified model that at every moment considered uniform distribution of the Joule losses within melt (in fact, this is an acceptable assumption, because movement of melt strongly contributes to uniformity of its parameters). Even so, processing of the task takes a lot of time.

Electrical and thermal computations were carried out in the environment of ANSYS, the shape of free surface being determined by means of own code written in Matlab in cooperation with ANSYS. The number of elements for electromagnetic field was about 80000, for temperature field about 12300 elements. Carefully was investigated the geometrical convergence of results and the influence of the artificial boundary (its radius was 5 m). In computation of free level deformation we used 1000 elements for the surface discretization.

Cooperation between environments for electromagnetic and thermal computations (ANSYS) and system for other calculations (Matlab) was realized by means of text files with all important data. The main procedure (written in Matlab) controls the run of simulations and provides the transfer of the data between both environments. For selected frequencies we started with undeformed shape of the surface and calculated the distribution of magnetic flux density on the surface. This distribution was redirected to Matlab in order to find modified shape of free surface (8). Then the new shape of level was used for next electromagnetic calculations. This process is repeated iteratively in order to find the balance given by (8). From the viewpoint of effectiveness it is necessary to realize this process automatically.

3. Results and their discussion

The arrangement depicted in Fig. 1 was solved for the following list of parameters:

- Molten steel: specific mass $\rho = 7800\,\mathrm{kg/m^3}$, relative permeability $\mu_\mathrm{r} = 1$, electrical conductivity $\gamma = 0.285714 \cdot 10^6$ S/m, thermal conductivity $\lambda = 36.2$ W/mK, surface tension $\sigma = 1.5\,\mathrm{N/m}$.
- Cylindrical fire-clay crucible with lid: $\lambda = 1.3\,\mathrm{W/mK}$, $\alpha = 20\,\mathrm{W/m^2K}$, $\mu_\mathrm{r} = 1$.
- Field coil from copper: number of turns $N = 26$, electrical conductivity $\gamma = 5.7 \cdot 10^7$ S/m, surface temperature $T = 50$ °C, field current density and frequency variable. The coil is wound along the external surface of the crucible and consists of hollow copper conductor intensively cooled by water.
- The shielding cylinder consists of steel segments separated by electrically insulating spacers. Relative permeability of this material is considered constant ($\mu_\mathrm{r} = 1000$) while its electrical conductivity $\gamma = 0$.
- Ambient air: $T_\mathrm{ext} = 30$ °C.

The most important results are shown in Figs. 2–5. Fig. 2 contains details of magnetic field in the neighborhood of the metal level (still undeformed) and initial distribution of temperature field at the beginning of stirring process (reached by current of density $J_\mathrm{ext} = 1.5 \cdot 10^6$ A/m^2 and frequency $f = 180$ Hz). After reaching thermal balance of the system by selection of the suitable amplitude of field current we started modeling of the heating process. The obtained temperature field represents the initial condition of the transient thermal analysis. We solved the process for several source currents (at frequency $f = 180$ Hz) and evaluated the increase of average temperature of melt. The magnetic field distribution was recalculated after fixed temperature increase in order to respect changes of material properties. As discussed in the previous paragraph we considered uniform distribution of the Joule losses within melt.

Figs. 3 and 4 show distributions of magnetic flux density along the radius of the melt level and corresponding changes of the melt level. These shapes of level (particularly for higher curvatures) may affect the time evolution of the velocity field, particularly near the level and crucible walls.

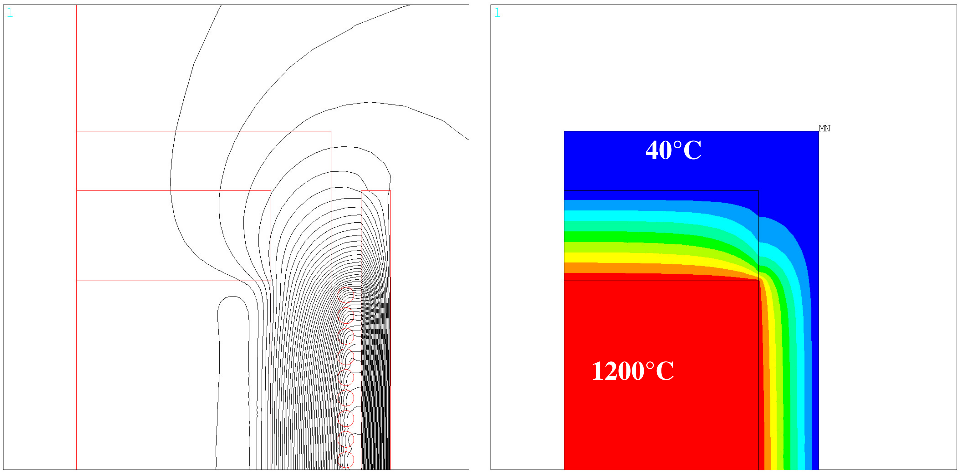

Fig. 2: Detail of distribution of magnetic flux lines and corresponding temperature field at the beginning of the process ($J_{ext} = 1.5 \cdot 10^6$ A/m^2, $f = 180$ Hz)

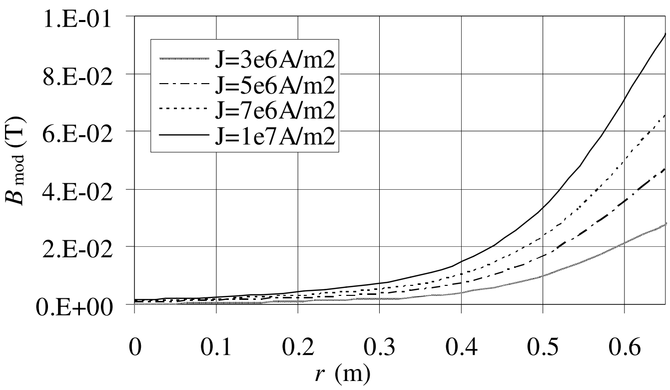

Fig. 3: Distribution of the module of magnetic flux density along the radius of the level for variable amplitude of field current density ($f = 180$ Hz)

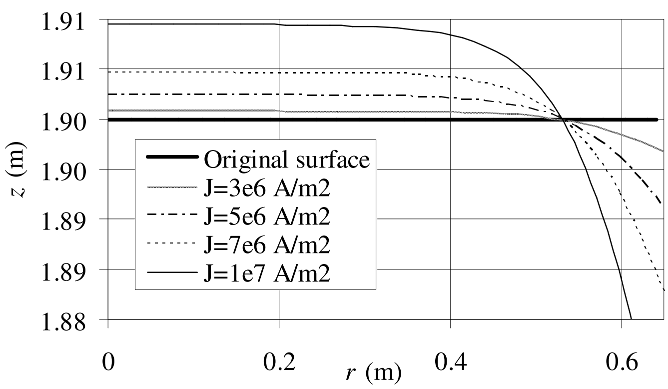

Fig.4: The shape of the level of melt for variable amplitude of field current density ($f = 180$ Hz)

Fig. 5 shows the main results of modeling – time evolution of the average temperature of melt. As can be seen, the whole process takes tens of minutes.

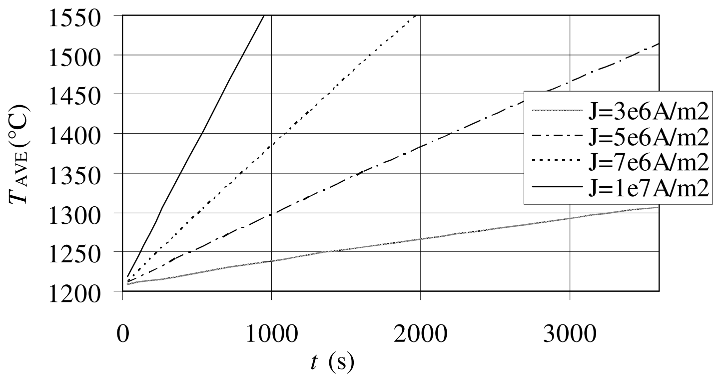

Fig. 5: Time evolution of average temperature in the melt

Conclusions

Mathematical and computer modeling of phenomena connected with electromagnetic treatment of molten metals is still a challenge. Even when it is possible to make use of existing knowledge and algorithms (for example for numerical solution of electromagnetic and temperature fields) implemented in professional codes such as Matlab and ANSYS, it is always necessary to write a lot of own procedures (in order to find the shape of the level etc.) and scripts for cooperation between various programs.

Of course, the methodology is still far from being complete. The further research will be aimed at effective computation of flow field (using, for instance FLUENT) and implementation of the corresponding algorithms to the system.

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