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Coupled Temperature-electromagnetic – Flow Fields in Electromagnetic Stirrer with Rotating Magnetic Field

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Abstract

The paper presents mathematical and computer modelling of weakly-coupled multiphysic fields describing the process of electromagnetic stirring realized by in-mould electromagnetic stirrer with rotating magnetic field. Temperature field was analyzed along the whole continual casting line in order to determine a real value of thickness of solidified layer of the axis-symmetric steel ingot. Then for known configuration of inductor-workpiece system electromagnetic field was calculated and based upon that the distribution of specific Lorentz forces in a whole area of liquid steel is determined. Finally flow field was analyzed and a distribution of liquid steel velocity was calculated. FEM-based software supplemented by single-owned numerical procedures elaborated by the authors was used for the computations. The next work in the area should be aimed at increasing accuracy of the calculations.

Introduction

Electromagnetic stirring of liquid metals in ladles, induction furnaces and in continual casting lines belongs to energy-saving, environment-friendly effective metallurgical processes used in modern ferrous and non-ferrous industry. The paper was concentrated on mathematical and computer modelling of electromagnetic stirring during the process of continual steel casting line. Coupled multi-physics fields were analyzed in an area of mould of such a line where Mould Electromagnetic Stirrer with rotating electromagnetic field was installed. The main purpose of the stirrer was a production of intensive, additional movement of liquid phase of the steel making possible to shorten time necessary for equalization of temperature distribution within the ingot and homogenization of its chemical composition [1-4].

A scheme of a classical continual steel casting line equipped with electromagnetic stirrers was presented in Figure 1. Molten steel was treated in the ladle (1) and in the tundish (2). Then it was tapped through the outlet (3) into a copper water-cooled mould (4), where the solidification was begun. Intensive cooling was continued along the secondary cooling zone (6). Finally solidified ingot (9) was cut. Three types of electromagnetic stirrers were installed along the steel continual casting line. The first of them called mould electromagnetic stirrer (5) (shortly MEMS) producing rotating magnetic field was generally installed inside the mould (4). The second stirrer: strand electromagnetic stirrer (7) (shortly SEMS) producing travelling magnetic field was placed below the mould in an area of secondary cooling. The last stirrer: final electromagnetic stirrer (8) (shortly FEMS) producing rotating magnetic field was located in a lower part of the line, where content of liquid steel was already rather small. Distribution of specific electromagnetic forces produced as a result of interaction between electromagnetic field and eddy currents within liquid metal was influenced on velocity distribution and in fact finally decided about intensity of stirring. It could change by regulation of inductor current and its frequency. Important role plays also location of the device along the line because of continual decreasing of liquid phase of steel with the increased distance from the mould.

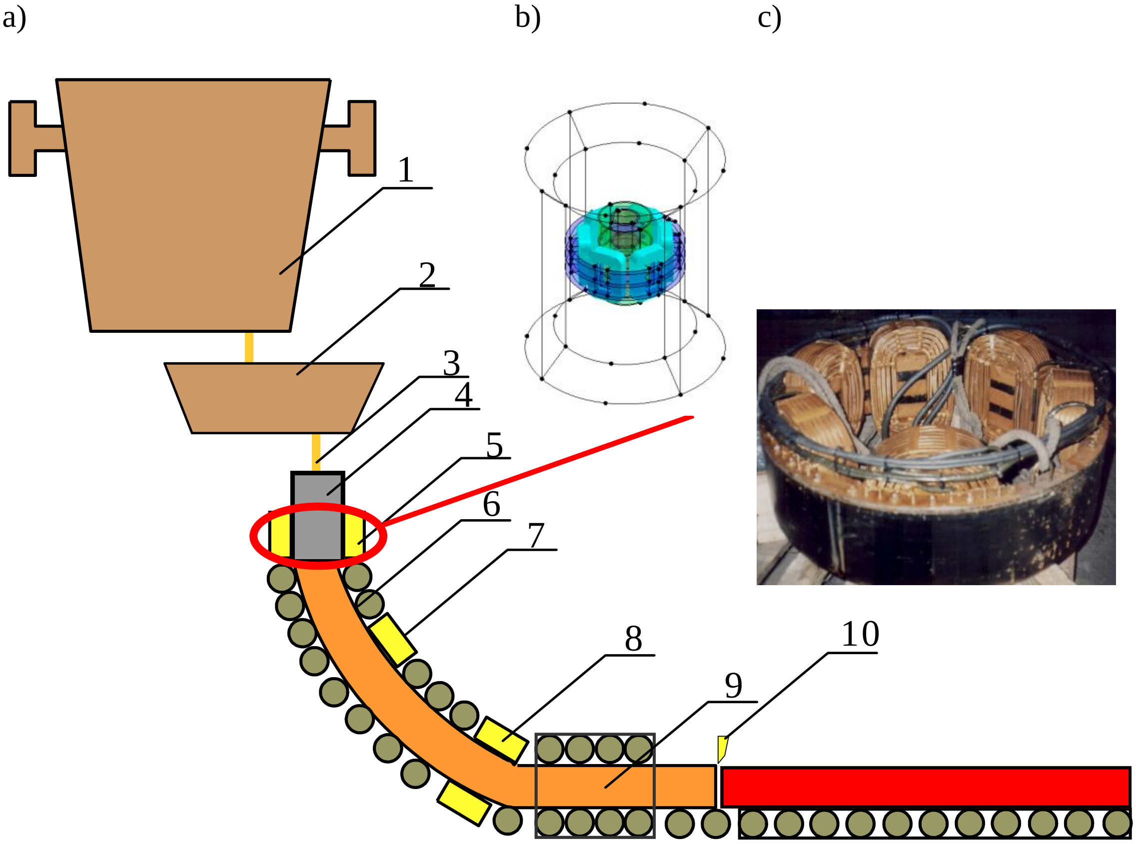

Fig.1. Continual casting line with three electromagnetic stirrers: a) scheme of the line 1 – ladle, 2 - tundish, 3 – outlet, 4 – mould, 5 – MEMS stirrer, 6 – cooling zone, 7 – SEMS stirrer, 8 – FEMS stirrer, 9 – solidified ingot and rolling system, 10 – cutting machine b, c) model and view of MEMS stirrer

This particular paper was concentrated on phenomena taking place in an area of MEMS stirrer picked in Figure 1 with red line.

1. Mathematical Model

The analyzed model of electromagnetic stirring deals with the weakly-coupled temperature, electromagnetic and flow field. Temperature field should be analyzed along the whole steel continual casting line in order to determine decreasing thickness of solidified layer of the ingot along the length of the casting line (increasing distance from the free liquid ingot surface in the mould). Computations start with the determination of temperature field distribution. The temperature distribution was described by Fourier-Kirchhoff equation:

$$\operatorname{div}\ \lambda \cdot \operatorname{grad} T\ - \rho c\ \ \mathbf{v}\operatorname{grad} T\ - \rho c \frac{\partial T}{\partial t} = -p_{\mathrm{v}}, \qquad (1.1)$$

where T denotes temperature, λ - specific thermal conductivity, ρ - density, c – specific heat, $\mathbf{v}$ – velocity, and p_{v} total specific external heat source.

Boundary conditions having both convection and radiation were taken into consideration [4] However for a simplified analysis presented in the paper it was assumed that electromagnetic field was not influenced on temperature distribution within the ingot, so p_v could be considered as zero also in area of electromagnetic stirrers. Analysis of temperature field makes it possible to determine thickness of solidified layer of the ingot b in dependence of distance from the liquid metal free surface in the mould.

In order to shorten a time of computations electromagnetic field was considered in a simplified way as quasi-stationary field and was given by the solution for the phasor $\underline{\boldsymbol{A}}$ of the magnetic vector potential $\boldsymbol{A}$

$$\mathrm{curl}\,\mathrm{curl}\,\underline{\boldsymbol{A}} + \mathrm{j}\cdot\omega\mu\gamma\underline{\boldsymbol{A}} + \gamma v\times\mathrm{curl}\,\underline{\boldsymbol{A}} = \mu\cdot\underline{\boldsymbol{J}}_{\mathrm{z}}\,, \tag{1.2}$$

where μ denotes magnetic permeability, γ - conductivity, $\boldsymbol{J}_{\mathrm{Z}}$ - vector of the external current density in the field coil., j - the imaginary unit, ω - the angular frequency.

Due to relatively low velocity of liquid metal movement the third term of the equation (1.2) can be neglected [5] and the equation was transformed into the classical form of the Helmholtz equation:

$$\mathrm{curl}\,\mathrm{curl}\underline{\boldsymbol{A}} + \mathrm{j}\ \omega\mu\gamma\underline{\boldsymbol{A}} = \mu\cdot\underline{\boldsymbol{J}}_{\mathrm{z}}\,, \tag{1.3}$$

The conditions along the axis of the electromagnetic stirrer and on the artificial boundary placed far enough from the inductor-workpiece system were the Dirichlet type ($\underline{\boldsymbol{A}} = \underline{\boldsymbol{0}}$). As the MEMS stirrer may be considered axis-symmetric, the magnetic vector potential $\boldsymbol{A}$ has only the tangential component. The phasor of eddy currents density produced in liquid steel and the specific Lorentz forces were given as:

$$\underline{\boldsymbol{J}}_{\mathrm{eddy}} = \mathrm{j}\cdot\omega\gamma\underline{\boldsymbol{A}}\ ; \tag{1.4}$$

$$\boldsymbol{f}_{\mathrm{e}} = \mathrm{Re}\left\{\underline{\boldsymbol{J}}_{\mathrm{eddy}}\times\mathrm{curl}\underline{\boldsymbol{A}}^{*}\right\}, \tag{1.5}$$

where $\underline{\boldsymbol{A}}^{*}$ denotes the complex conjugate to $\underline{\boldsymbol{A}}$.

The system of Navier-Stokes and continuity equations describes the motion of liquid metal:

$$\rho[\frac{\partial\boldsymbol{v}}{\partial t} + (\boldsymbol{v}\cdot\mathrm{grad})\boldsymbol{v}] = -\,\mathrm{grad}\ p + \rho\,\mathbf{g} + \frac{\eta_{\mathrm{d}}}{\rho}\cdot\Delta\boldsymbol{v} + \boldsymbol{f}_{\mathrm{e}}\ ; \tag{1.6}$$

$$\mathrm{div}\ \rho\boldsymbol{v} = 0\,, \tag{1.7}$$

where p denotes pressure, $\boldsymbol{g}$ – gravity acceleration and η_{d} - dynamic viscosity.

Due to turbulent character of the liquid metal flow the dynamic viscosity was determined based upon k - ε model [6]. The mathematical model presented above was solved by a combination of different FEM-based professional software supplemented by single-owned procedures elaborated by the authors. A way of the temperature calculations was described in

[6]. For analysis of electromagnetic field Matlab and/or Flux 2D/3D packages were applied, however for flow field the Fluent 2 D program was used. A special emphasis was put on the convergence of results in the dependence of the position of the external artificial boundary with zero Dirichlet condition. Numerical modelling of one computation cycle takes approximately several minutes.

2. Illustrative Example

The theoretical analysis of coupled temperature – electromagnetic - flow fields was supplemented by an illustrative example dealing with the MEMS electromagnetic stirrer located at a beginning of the continual casting line in an area of mould (the MEMS stirrer). The distribution of liquid steel velocity was determined on the basis of the described mathematical model. Some input data applied for computations were shown below:

Magnetic core:
- electric conductivity $\gamma = 0$
- relative magnetic permeability $\mu_r = 100$

Solidified part of ingot:
- electric conductivity $\gamma = 0{,}868 \cdot 10^6$ S/m
- relative magnetic permeability $\mu_r = 1$
- temperature $T = 1540\ ^oC$
- casting speed $v_c = 0.05$ m/s
- density $\rho = 6920$ kg/m^3
- dynamic viscosity $\eta_d = 6.15 \cdot 10^5$ N/s
- diameter of the ingot $D = 0.17$ m

Liquid part of ingot:
- electric conductivity $\gamma = 0.757 \cdot 10^6$ S/m
- relative magnetic permeability $\mu_r = 1$

Coils:
- electric conductivity $\gamma = 5.5 \cdot 10^7$ S/m
- relative magnetic permeability $\mu_r = 1$
- field current $I = 284$ A
- number of turns $n = 88$,
- frequency $f = 4.5$ Hz

Distribution of the specific Lorentz forces within liquid metal in the area where the MEMS stirrer installed was shown in Figure 3. Based upon obtained distribution of specific Lorentz forces in liquid phase of molten steel a distribution of velocity was determined. Some results of flow field computations were shown in Figures 4 - 5. Distribution of tangent component of velocity on direction of z axis (along the length of the MEMS stirrer) was shown in Figure 4. Distribution of tangent component of velocity in radial direction (in cross-section of liquid ingot) for five different positions along the length of the mould was shown in Fig.5. More results of flow field calculations for different parameters of the inductor-workpiece of the MEMS electromagnetic stirrer system will be presented during the seminar.

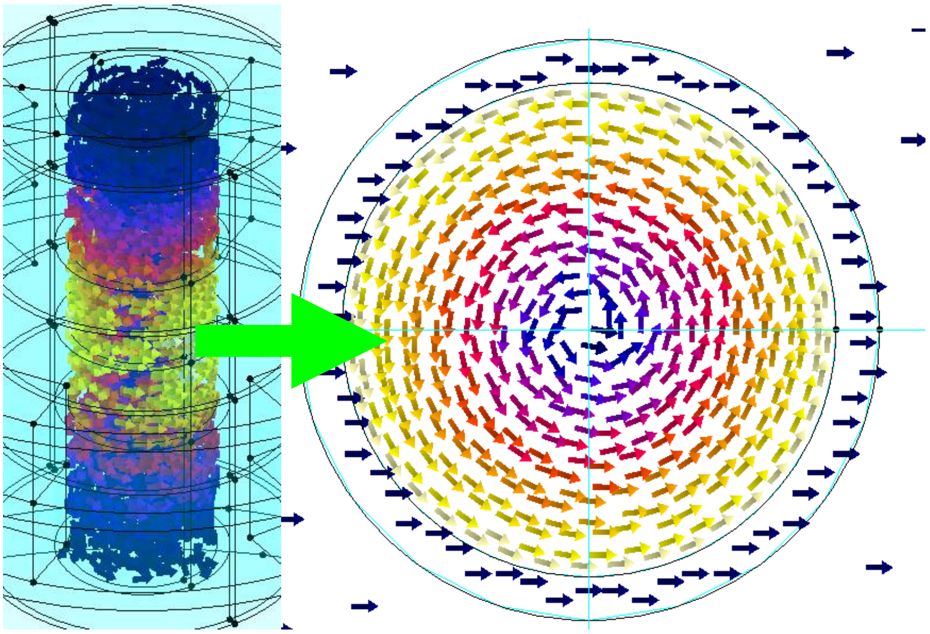

Fig. 3. Distribution of specific Lorentz forces in liquid part of the steel ingot at low frequency *f* = 4.5 Hz

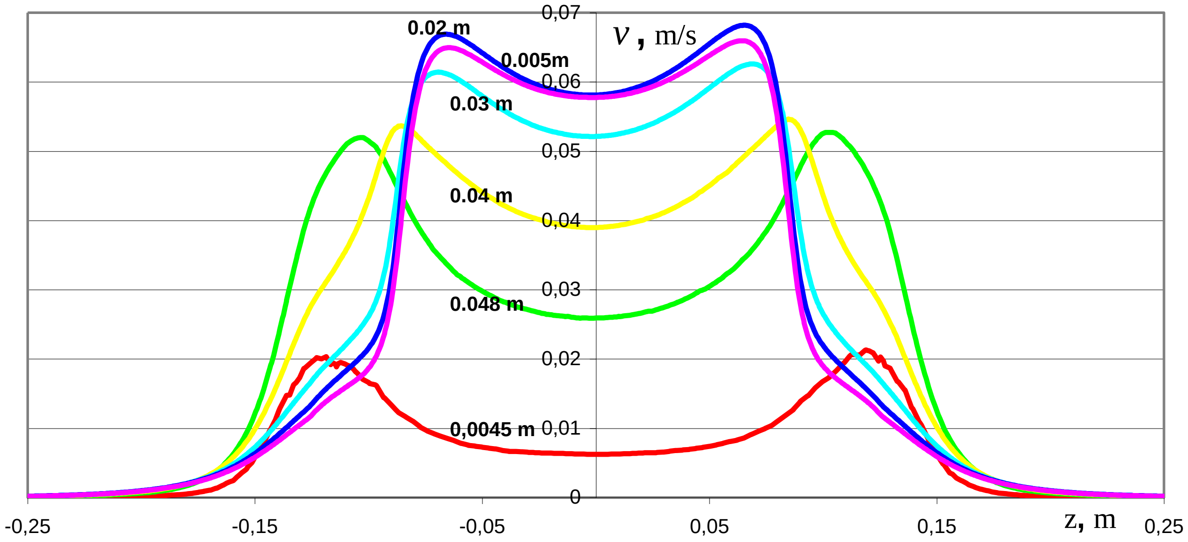

Fig. 4. Distribution of tangent component of liquid steel velocity in direction of *z* axis (along the length of the MEMS stirrer) for six different distances from axis of the ingot

Conclusions

Mathematical modelling of weakly-coupled temperature-electromagnetic-flow fields during electromagnetic stirring of liquid steel in a process of its continual casting of cylindrical ingots was presented in the paper. Professional software, mainly Flux and Fluent packages which was used for the computations, was supplemented by own-single numerical procedures elaborated by the authors. Calculations were done for MEMS stirrer installed inside the mould. The results of calculations contain the distribution of the specific Lorentz forces and velocity within the liquid ingot. The presented methodology makes it possible to analyze intensity of electromagnetic stirring.

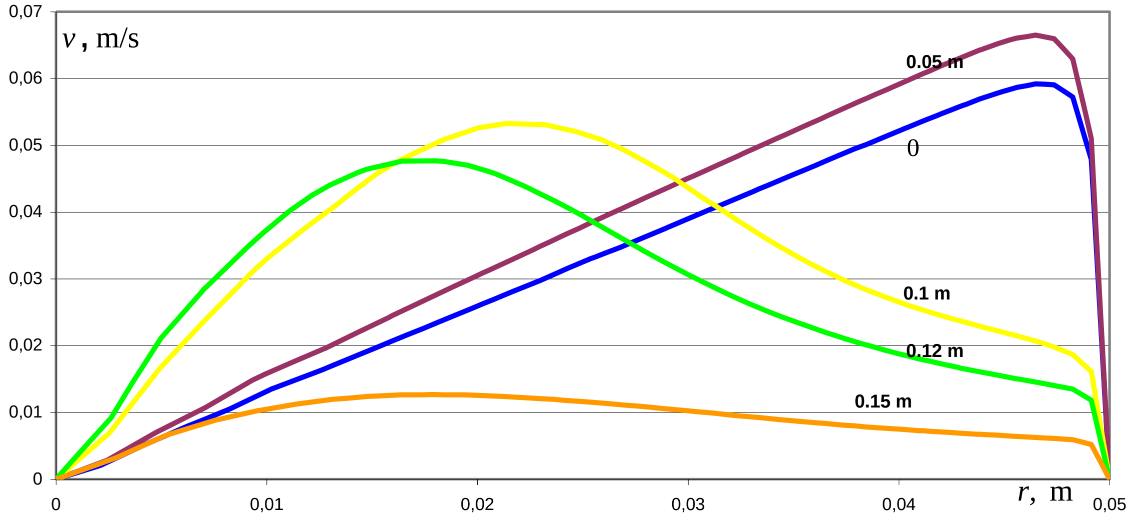

Fig. 5. Distribution of tangent component of liquid steel velocity in an area of MEMS stirrer in radial direction for five different positions along the length of the stirrer

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References

[1] Barglik, J., Golak, S., Pragłowska-Gorczyńska, Z., Przyłucki, R., Smagór, A.: *Magnetohydrodynamics in metallurgical Applications*. Proceedings of the 10th International Conference "Electric Power Engineering", 2009.

[2] Barglik, J., Smagór, A.: *Some aspects of electromagnetic stirring process of continual steel casting*. Proceedings of the 6th International Conference on Processing of Materials. Dresden , 2009, pp. 684-687.

[3]. Barglik, J., Czerwiński, M., Hering, M., Wesołowski, M.: *Radiation in Modelling of Induction Heating Systems*. IOS Press Amsterdam, Berlin, Oxford, Tokyo, Washington DC, 2008, pp. 202-211.

[4] Barglik, J., Dołęga, D., Smagór, A.: *Mathematical modelling of electromagnetic stirring during process of continual steel casting.* Proceedings of the HES 2010. Padua , 2010, pp. 19-26.

[5] Barglik, J., Doležel, I., Ulrych, B.: *Induction heating of moving materials.* Acta Technica CSAV, Academy of Sciences of the Czech Republic, Prague, Vol. 43, 1998, pp. 515-527.

[6] Sajdak, C., Mazur, A.: *Simulation of solidification of liquid steel ingots*. Proceedings of the International Conference - "Iron&Steelmaking", 2006.

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