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Abstract
To improve the quality of the electromagnetic stirring of liquid metal periodically alternate a force to the metal of the traveling and the pulsating magnetic fields has been proposed. Two constructions of the electromagnetic stirrer of the metal in the form of two-limb and three-limb inductors are considered, that allow implementing of such a method of stirring due to the periodic alternation of their multiphase and single-phase power supply. With reference to reverberatory furnace for aluminum based on the 3D computer modeling electromagnetic and hydrodynamic processes in the system "inductor – a bath of liquid metal" have been investigated. It is shown, that in the case of multiphase power supply both inductors produce in the furnace bath single-circuit vortical flow of metal, but in the case of single-phase power supply – dual-circuit vortical flow. Thus stagnant zones of metal that presents in one mode are effectively stirred in another. The durations of transient hydrodynamic processes have been identified. A comparative assessment of the effectiveness of such stirrers for different modes of operation has been executed.

Key words: electromagnetic stirrer of liquid metal, traveling and pulsating magnetic fields, two-limb and three-limb inductors, single-circuit and dual-circuit vortical flows, computer modeling.

Introduction
Stirring of liquid metal is important technological process, which is performed during the melting of metals and alloys preparation on purpose to intensify technological processes and improve the quality of cast billets. Such operation is carried out mainly by the three-phase or two-phase electromagnetic stirrers that create traveling or rotating magnetic fields [1, 2]. Especially acute need for stirring the melt, as known, occurs in reverberatory furnaces and mixers a heat source of metal in which is located on the top (above the surface). Frequently in such cases electromagnetic stirrer of traveling magnetic field is used, that attaches to the sidewall of the furnace bath, whereby in it a single-circuit vortical flow of liquid metal is created. Such flow involves in motion mostly peripherals (parietal) layers of metal. In the central part of the bath stagnation zone is formed in which metal is not sufficiently stirred. The situation may be improved by using an electromagnetic stirrer with a pulsating magnetic field [3]. Such stirrer, unlike stirrer with a traveling magnetic field, creates a dual-circuit vortical flow in the bath, which effectively stirs just the central zone of furnace bath (Fig. 1).

Fig. 1: Sketch of the bath of the reverberatory furnace with electromagnetic stirrer of pulsating magnetic field

In order to further improving of the quality of stirring of the metal melt in the reverberatory furnace bath it is proposed to use alternating electromagnetic effect on the liquid metal of traveling and pulsating magnetic fields [4]. Is obvious that if periodically to alternate single-circuit and dual-circuit vortical flows it result to the more qualitative stirring of liquid metal in the entire volume of the furnace bath. Stagnant zones that occur in one mode of operation will be effectively mixed with the other mode.
For realization of such method of stirring, electromagnetic stirrer, which is able to create these flow structures, is required. Such stirrer may be obtained by the inductors basis with two-limb and three-limb magnetic cores (C- and E-shaped cores), on each limb of which are arranged electrical coils (Fig. 2). By connecting each of these inductors to a single-phase voltage in the liquid metal of the furnace is excited pulsating magnetic field, and in the case of multiphase power supply – traveling magnetic field.

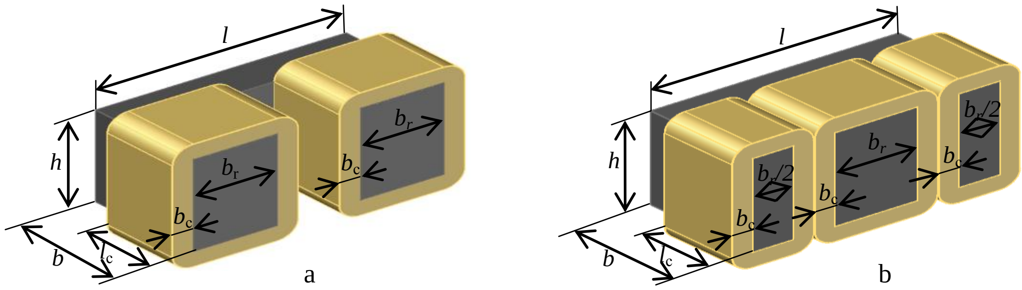

Fig. 2: Two-limb and three-limb inductors

The aim of this work is to carry out research of electromagnetic and hydrodynamic processes in the system "inductor – bath with liquid metal" for the above design solutions of the electromagnetic stirrer in relation to the reverberatory aluminum furnace based on the 3D computer modeling.

Formulation of the problem

Studies were performed on the basis of the numerical solution of the problems of the electromagnetic field and fluid dynamics for each of the electromagnetic system of the stirrer for their single-phase and multiphase power supply. The calculation of the hydrodynamic flow of the liquid metal was carried out for both steady state and unsteady (transient) conditions, which occur by switching from one type of power supply to another.

In formulating electromagnetic problem the following simplifying assumptions were taken. The system was considered in the linear approximation. Laminated magnetic core of each inductor was considered electrically non-conductive, magnetic permeability of it is taken constant and hysteresis loss and eddy currents were neglected. Real inhomogeneous structure of coils containing conductive (wires) and non-conductive (frame of coil, insulation) elements was represented a homogeneous non-conductive environment with a uniformly distributed and predetermined current density. Calculations were performed in non-inductive approach excluding the electromotive forces induced in the liquid metal due to its movement. This approximation was based on the evaluation of the magnetic Reynolds number $\mathrm{Re_m}$, the value of which in this case turned out to be much less than one.

The calculation of the electromagnetic field was carried out by the numerical solution of differential equations for the complex amplitudes of the magnetic vector $\dot{\mathbf{A}}$ and electric scalar $\dot{\varphi}$ potentials

$$\nabla \times (\mu_0^{-1}\mu_r^{-1}\nabla \times \dot{\mathbf{A}}) + (j\omega\sigma - \omega^2\varepsilon_0\varepsilon_r)\dot{\mathbf{A}} + (\sigma + j\omega\varepsilon_0\varepsilon_r)\nabla\dot{\varphi} = \dot{\mathbf{J}}_e \,, \qquad (1)$$

where μ_0 and ε_0 – permeability and permittivity of vacuum, μ_r and ε_r – relative permeability and relative permittivity, σ – electrical conductivity, ω – angular frequency, $\dot{\mathbf{J}}_e$ – the complex amplitude of the external current density with a given distribution.

The hydrodynamic problem was solved for the area of the liquid metal in the bath of the furnace. The velocity distribution of the melt was determined by means of numerical solution of differential Navies-Stokes equations for viscous turbulent flow

$$\rho_m \frac{\partial \mathbf{u}}{\partial t} + \rho_m(\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \nabla\cdot\left(\eta_{eff}\nabla\mathbf{u}\right) + \mathbf{f} \;; \qquad (2)$$

$$\nabla\cdot\mathbf{u} = 0 \,, \qquad (3)$$

where $\mathbf{u}$ – the velocity of the liquid metal, ρ_m – metal density, p – pressure, η_{eff} – effectiveness ratio of the dynamic viscosity of the metal, determined using k-ε turbulence model, $\mathbf{f}$ – specific electromagnetic forces in the liquid metal, calculated by solving the electromagnetic problem. The boundary conditions on the walls of the furnace bath were set in the form of logarithmic velocity profile for the boundary layer. To simplify the problem the same condition was assumed on the upper surface, that allowed to exclude from consideration the deformation of the free surface of the liquid metal in bath. The equations (2, 3) were solved for both stationary ($\partial\mathbf{u}/\partial t = 0$) and non-stationary ($\partial\mathbf{u}/\partial t \neq 0$) flow regimes.

The hydrodynamic efficiency of both design variants of the stirrer and of their operation modes was estimated by averaging over the entire volume of the liquid metal V_m melt rate

$$W = \frac{1}{V_m} \int_{V_m} \sqrt{u_x^2 + u_y^2 + u_z^2}\, dV . \tag{4}$$

As criterion of efficiency, taking into account both the hydrodynamic "performance" and power of the stirrer, was taken relation $W_S = W/S^{1/2}$, where S – electromagnetic power, determined from the calculation results of the electromagnetic field in accordance with the expression

$$S = \mathrm{Abs}(\tilde{S}) = \mathrm{Abs}(j\omega \frac{1}{2} \int_{V_c} \dot{\mathbf{A}} \overset{*}{\mathbf{J}} dV) . \tag{5}$$

Here $\tilde{S}$ – complex electromagnetic power, V_c – volume of stirrer coils. The real part $\tilde{S}$ in the case of inductionless approximately is equal to the power of heat from eddy currents in the liquid metal. Imaginary part $\tilde{S}$ corresponds to the reactive power of the electromagnetic system.

Possibility of taking W_S as a generalized specific criterion of stirrer efficiency is caused by turbulent motion of the melt in the furnaces during electromagnetic stirring. Since the friction force herewith, as known, is proportional to velocity squared, and electromagnetic forces in the melt is proportional to ampere-turns of the inductor to the square, then the result the speed of the melt will be proportional to ampere-turns and, respectively, to the square root of inductor power. Thus, for each version of design of the stirrer selected criterion of efficiency W_S will remain constant for all values of ampere-turns.

Discussion of the results of simulation

Simulation of electromagnetic and hydrodynamic processes was carried out at the following initial data. The volume of liquid metal (aluminum) located in the furnace bath is $(3 \times 2 \times 0.5)$ m^3. The location of inductors at the side wall of the furnace bath was considered symmetrically with respect to the metal both in length and height, at a distance there from of 0.1 m. It was considered that between the inductor and the liquid metal there is a non-conductive insulating wall. The basic geometrical sizes that are shown in Fig. 2, for both inductors were taken the same. They constitute: core length l = 0.6 m, width b = 0.3 m, its height h = 0.3 m, the width and the length of the limb (rod) – b_r = 0.2 m and l_r = 0.2 m. The size of coils are equal, their length l_c equal to the length of the rod l_r, and the cross-sectional width b_c = 0.05 m.

All calculations were performed during power supply of stirrers by current of industrial frequency ($\omega = 2\pi \cdot 50$ 1/s) at predetermined the total ampere-turns of all stirrer coils, which are uniformly distributed over the coils. It was assumed that the peak value of these ampere-turns for each stirrer $\sum_{i=1}^{n} I_i w_i = 60\,\mathrm{kA}$ (n – the number of stirrer coils). Herewith the value of the current density in the coils computational domain was set as the $J_e = I_i w_i / (l_c b_c)$. In the pulsed magnetic field mode currents in adjacent coils of both stirrers were knitted among themselves at an angle ψ_I = 180 e. deg., and in the mode of traveling field considered two variants, when this angle is 60 and 120 e. deg.

As a result of calculation in such a way was found that both stirrers in case of single-phase power supply (ψ_I = 180 e. deg.) creates in the bath furnace dual-circuit vortical flows of the liquid metal, and when the multiphase power supply (as in the case of ψ_I = 60 e. deg., and when ψ_I = 120 e. deg.) – single-circuit.

In Fig. 3 the structures of the metal flow (velocity field) in the average height sectional volume of the liquid metal for the three-limb stirrer are shown. Fig. 3a refers to single-phase power stirrer, Fig. 3b – to three-phase power of the stirrer with the phase shift angle between the neighboring coils ψ_I = 60 e. deg. Qualitatively similar form has also metal flow in the case of two-limb stirrer.

The numerical solution of nonstationary hydrodynamic problem make possible to trace in time transformation of vortex flows in furnace bath during changing power supply regiments. In reference [5] you can see the video, which demonstrates the calculated picture of the flow of molten aluminum in the bath furnace as velocity fields generated by the alternate action of the pulsating and traveling magnetic fields for the three-limb inductor. Initially, this video shows how under the influence of a pulsed magnetic field established dual-circuit vortical flow of liquid metal in the bath when to single-phase power inductor is applied. Then inductor switches to the three-phase power supply, resulting in dual-circuit flow transforming to a single-circuit flow. After that by switching back of the inductor to a single-phase power supply the flow is transformed in dual-circuit flow again. And for the completion demonstrates transformation of dual-circuit flow of metal to the single-circuit reverse direction flow when switching to the three-phase power supply with phase reversal (compared with the previous case).

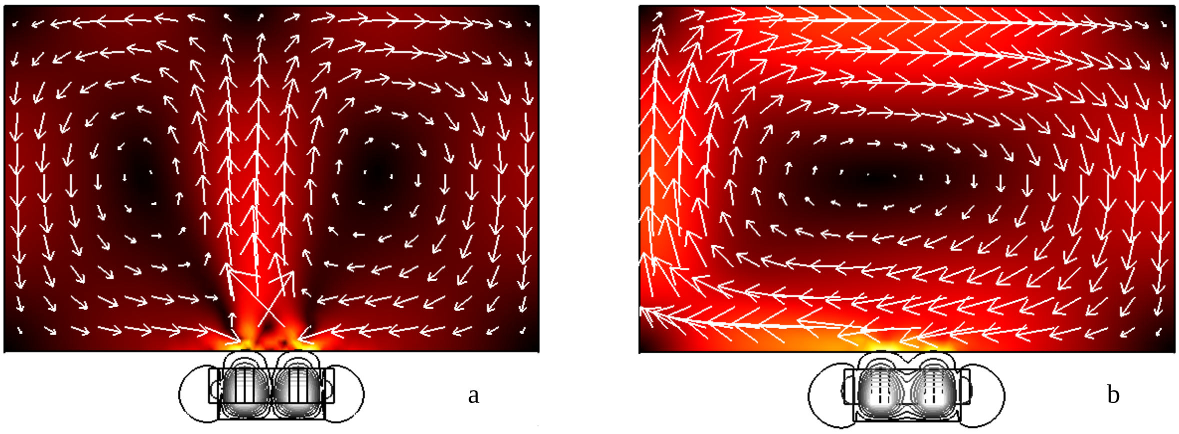

Fig. 3: The flow of liquid metal in the furnace bath under the action of the pulsing (a) and traveling (b) magnetic fields

When applying single-phase power supply on every stirrer the establishing time of dual-circuit flow of the metal in the bath with the above sizes was about 100 s, and when they are connected to the multi-phase power supply establishing time of the single-circuit flow was ~150 s. When switching the stirrer from one to the other flow mode transition process time (time of transition from one steady state to another) was approximately equal to 120 s. At unsteady hydrodynamic calculations it was neglected of transient electromagnetic processes, during switching power supply of the inductor, because of their relatively shortness.

The table below shows the obtained estimated values of key parameters of two-limb and three-limb inductors, where S – electromagnetic power of the stirrer, P_m – power dissipated in the liquid metal in the form of Joule heat, B – average magnetic induction in the magnetic core. Analyzing the table data, it should be noted that both stirrers are more efficient in the mode of traveling magnetic field when two-limb stirrer powered by a two-phase voltage and three-limb stirrer – by a three-phase power supply. This follows both from the average speed W and from the criterion of W_S. Comparing these inductors together at the mode of pulsed magnetic field turned out to be more effective stirrer with two limbs, and in the mode of traveling field it is three-limb stirrer. As for the multi-phase power mode with different phase angles ψ_I, then, based on the criterion of W_S, the work of two stirrers at an angle ψ_I = 60 e. deg. is more effective according to the obtained data.

Table

ψ_I, e. deg.	Two-limb inductor					Three-limb inductor				
	W, m/sec	W_S, m/(sec·kVA$^{1/2}$)	S, kVA	P_m, kW	B, T	W, m/sec	W_S, m/(s·kVA$^{1/2}$)	S, kVA	P_m, kW	B, T
180	0.1	0.0054	410	14.9	0.87	0.08	0.0043	358	10.6	0.94
60	0.12	0.0076	254.5	7.1	0.53	0.24	0.0185	164	4.4	0.56
120	0.118	0.0062	358.1	10.3	0.77	0.27	0.0155	301	6.8	0.86

Conclusions

Thus, represented designs of inductors, which are able to separately create pulsating and traveling magnetic fields that allow to implement a new method of electromagnetic stirring of liquid metal in the bath of reverberatory furnace by alternately (periodically) change the structure of the vortex flow. The analysis shows that both constructs of the electromagnetic stirrer are approximately equal in efficiency. The final choice in favor of any decision can be made on the basis of the review and including technological aspects of the stirring process, evaluation of the technical capabilities of the power supply system and other features.

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