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ELECTROMAGNETIC STIRRING OF METALS IN SPATIALLY ORTHOGONAL MAGNETIC FIELDS

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A mathematical model and a method for calculating the parameters of an electromagnetic system with spatially orthogonal magnetic fields, which are created by the currents of two windings, one of which is made in the form of a cylindrical inductor, and the second in the form of a saddle-shaped coil with linear sections directed along the generatrix of the inductor, are developed. The average volume densities of electromagnetic forces causing the melt motion during induction heating in crucible furnaces or continuous casting machines of steel billets are determined. It was established that at the level of large radial velocities insignificant velocity inhomogeneities take place, which together with the azimuthal velocity leads to the appearance of velocity vortices and contributes to additional mixing of the metal. The windings supply voltage of the considered electromagnetic device is determined, which ensures the stirring of liquid metal at the final stage of the continuously cast ingot production. References 9, figures 3.
Key words: molten metal, electromagnetic stirring, electromagnetic force.

Introduction. Electromagnetic stirring of metals is widely used in many technological processes, both for the intensification of production, and directly to improve the quality of the metal in the processes of metallurgical conversion. As a result of metal stirring, the heat and mass transfer of the liquid metal increases, the temperature gradient decreases, which leads to equalization of the chemical composition and intensification of heat transfer both in volume of the liquid phase and with the cooling environment. To intensify metal production processes, one use widespread methods of electromagnetic action on molten metal in billet continuous-casting machines as directly in the crystallizer, and in the secondary cooling zone – final stirrer. The last devices in its properties may differ significantly from the stirrers in the primary cooling zone (in the crystallizer zone).

The difference, first of all, is in the type of the metal melt motion. In the first case, the melt flow predominantly directed in azimuth, and the final electromagnetic stirrers force the molten metal to move in the axial direction. The type of electromagnetic stirring with the axial direction of liquid metal flow is also characteristic of other melting or metallurgical finishing devices – crucible melting furnaces, ladle-type devices, and others. The implementation of such electromagnetic stirrers is carried out mainly using multiphase electromagnetic system with a traveling magnetic field [1]. Their energy efficiency due to open magnetic cores and, therefore, large non-magnetic gaps is low, which is often a justified reason for the refusal of metallurgists to use the technology of electromagnetic mixing of metal. However, the search for possible solutions for electromagnetic stirrer is continuing, especially in new innovative technologies, such as the production of intermetallic composites for permanent magnets, complex alloys, etc. In [2], the technical solution of a single-phase electromagnetic stirrer with spatially orthogonal magnetic fields was analyzed and a mathematical model was proposed to describe the electromagnetic processes in it. General relations were obtained for calculating magnetic fields and analytical expressions for calculating electromagnetic forces.

Mathematical modeling of the influence of technological processes and design parameters on the effectiveness of electromagnetic exposure on liquid metal requires solving in the general case of three-

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dimensional boundary value problems for the Maxwell equations system in an unbounded domain, containing geometrically composite ferromagnetic and conductive bodies, Navier-Stokes equations in liquid metal, heat conduction equations. In some cases, it is possible to solve the problem in a plane-parallel and axisymmetric approximation. The application of analytical methods for solving such problems is possible only in the simplest cases and for estimating.

Currently, there are different approaches and methods for solving these problems: finite difference method [3], finite element method [4], integral equation method [5,6] and other methods that are effectively used for the numerical calculation of electromagnetic fields.

The design features of electrotechnical devices with liquid conductors are as follows, that applying the finite difference method or finite element method leads to a large amount of unnecessary calculations. This is due to the fact that in the considered devices have a strong magnetic scattering fields. To take them into account when using these methods, the computational domain size must be chosen in several times larger, than the characteristic size (e.g. diameter) of the devices. In this case, the magnetic field is calculated at all mesh node, which covers the computational domain, while there is no need for such complete information. From the point of view of reducing the solution search area, the method of integral equations has an advantage [6]. However, in the case of orthogonal magnetic fields that are excited by mutually perpendicular electromagnetic systems, the calculated solution search area is undefined. In this case, analytical methods for calculating magnetic fields, electromagnetic forces, and liquid metal speed are most in demand, especially for determining trends.

The aim of the work is to carry out comprehensive analysis of electromagnetic and hydrodynamic processes in a liquid metal stirrer with spatially orthogonal magnetic fields and to evaluate the melt movement character.

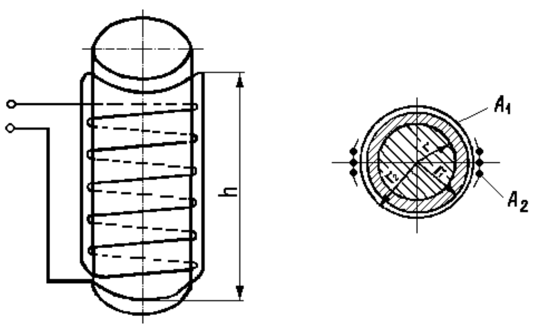


Fig. 1

Materials and results of the research. The essence of such stirrer implementation is that it consists of two windings, one of which is made in the form of a cylindrical inductor with radius r_2 and height h, and the second is made in the form of saddle-shaped coil with linear sections, which is directed along the inductor generatrix and concentrated within the central angle $2\varphi_1$ (Fig.1).

Using the example of a cylindrical ingot, it is assumed that the radius of the liquid phase of the ingot is r and it has electrical conductivity σ, and wall thickness crystallizer having an electrical conductivity σ_1 is $(r_1 - r)$. Applicable to final electromagnetic stirrers or skull crucibles r_1 is ingot radius or skull and σ_1 is electrical conductivity of the hardened part of the ingot or skull.

Current loads of each winding of the electromagnetic stirrer are described by dependencies [2]:

$$A_1 = \mathbf{e}_\phi \frac{Iw_1}{h} e^{i\omega t}\delta(r - r_2),\; A_2 = \mathbf{e}_z \frac{Iw_2}{2\varphi_1 r_2} e^{i\omega t}\delta(r - r_2)\left[\Theta(\varphi+\varphi_1) - \Theta(\varphi-\varphi_1) - \Theta(\varphi-\pi+\varphi_1) + \Theta(\varphi-\pi-\varphi_1)\right]. \quad (1)$$

Here $\mathbf{e}_\varphi$ and $\mathbf{e}_z$ are the unit vectors of the adopted cylindrical coordinate system; $\delta(\cdot)$ is Dirac delta function; $\Theta(\cdot)$ is the unit generalized function; w_1, w_2 are the first and second windings turns number. To simplify the writing, the successive connection of the stirrer windings with the same current I in the turns of both windings is accepted, which, however, does not lead to a violation of generality, since the relation between w_1 and w_2 is arbitrary.

The distribution of the magnetic field in each of the areas stirrer is described by the equation for the vector magnetic potential [8]

$$rot\, rotA = -\mu\sigma\left(\frac{\partial A}{\partial t} - v \times rotA\right), \quad (2)$$

μ and σ is magnetic permeability and electrical conductivity of the medium, traverse speed v of all medium except the melt is zero. Assuming that the electromagnetic field due to the motion of the melt is small compared with the field of excitation, to determine the electromagnetic forces in a liquid, we limit oneself to the electrodynamic approximation, accepting the speed $v = 0$ also for the liquid phase of the ingot. The last assumption is very crude and can only be justified in case of obtaining estimated results.

Excluding edge effects basic electromagnetic and hydraulic processes can be described in the framework of a model with infinite stirrer height, what becomes technically acceptable just at $h/r_2 \geq 4$.

With regard to the adopted model, vector equation (2) using Coulomb calibration ($divA = 0$) reduces to the second order independent differential equations system for the axial and azimuthal components of the vector magnetic potential

$$\frac{\partial^2 A_z}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial A_z}{\partial \rho} + \frac{1}{\rho^2}\frac{\partial^2 A_z}{\partial \varphi^2} - i\mu\sigma\omega A_z = 0,$$
$$\frac{\partial^2 A_\varphi}{\partial \rho^2} + \frac{1}{\rho}\frac{\partial A_\varphi}{\partial \rho} - \frac{A_\varphi}{\rho^2} - i\mu\sigma\omega A_\varphi = 0. \quad (3)$$

If $\rho = 0$ the above equations must satisfy the boundedness condition, and satisfy the following boundary conditions:

$$\frac{\partial A_z}{\partial \rho} = \mu A_2, \qquad \frac{1}{\rho}\frac{\partial(\rho A_\phi)}{\partial \rho} = \mu A_1 \quad (4)$$

and conjugation conditions (the continuity of the vector potential components and their normal derivatives) at the medium interfaces.

As a result of solving the second equation of the system (3) with boundary condition (4) the distribution of the azimuthal component magnetic potential in the liquid phase of the ingot $(\rho \leq r)$ described by addiction

$$A_\varphi = CI_1(a\rho), \quad (5)$$

Where $$C = \frac{\mu I w_1 r_1 e^{i\omega t}}{hI_1(ar)} \frac{I_1(a_1 r) - BK_1(a_1 r)}{I_1(a_1 r_1) - r_1 I_1'(a_1 r_1) - B\left[K_1(a_1 r_1) + r_1 K_1'(a_1 r_1)\right]};$$

$$B = \frac{I_1(a_1 r)I_1'(ar) - I_1(ar)I_1'(a_1 r)}{K_1(a_1 r)I_1'(ar) - I_1(ar)K_1'(a_1 r)}; \qquad a = \sqrt{i\mu\sigma\omega};\ a_1 = \sqrt{i\mu\sigma_1\omega};\ i = \sqrt{-1};\ \mu = 4\pi \cdot 10^{-7}\ \text{Гн/м},$$

$I_1(\ldots)$, $K_1(\ldots)$ are modified Bessel functions of the first and second kind, the prime denotes the derivative of the Bessel function of the radius.

The solution for the z-component of the magnetic potential in the area of the metal liquid phase (the first equation of system (3)) can be obtained after its integral transformation by the coordinate φ taking into account the periodicity conditions and it can be represented by series

$$A_z = \sum_{j=1}^{\infty} C_n I_n(a\rho)\cos n\varphi, \quad (6)$$

$$C_n = \frac{4\mu I w_2 r_1^n \sin n\varphi_1 e^{i\omega t}}{n\pi\varphi_1 r_2^n I_n(ar)} \frac{I_n(a_1 r) - B_n K_n(a_1 r)}{D_n},$$

$$B_n = \left[I_n(a_1 r)I_n'(ar) - I_n(ar)I_n'(a_1 r)\right] \times \left[K_n(a_1 r)I_n'(ar) - K_n'(a_1 r)I_n(ar)\right]^{-1},$$

$$n = 2j - 1,\ j = 1, 2, \cdots.$$

Depending on the design of the electromagnetic stirrer D_n it takes different values.

So in the presence of an external magnetic circuit

$$D_n = I_n(a_1 r_1)n\left(1 - \frac{r_1^{2n}}{r_2^{2n}}\right) + r_1 I_n'(a_1 r_1)\left(1 + \frac{r_1^{2n}}{r_2^{2n}}\right) - B_n\left(K_n(a_1 r_1)n\left(1 - \frac{r_1^{2n}}{r_2^{2n}}\right) + r_1 K_n'(a_1 r_1)\left(1 + \frac{r_1^{2n}}{r_2^{2n}}\right)\right),$$

and in its absence

$$D_n = 2\left(nI_n(a_1 r_1) + r_1 I_n'(a_1 r_1) - B_n\left(nK_n(a_1 r_1) + r_1 K_n'(a_1 r_1)\right)\right).$$

Based on the equations $\vec{B} = rot\,\vec{A}$, $\vec{E} = -\partial\vec{A}/\partial t$, $\vec{j} = \sigma\vec{E}$, without special difficulties, we get the distribution of magnetic induction in the melt

$$B_\rho = -\frac{1}{\rho}\sum_{j=1}^{\infty} C_n I_n(a\rho) n \sin n\varphi; \quad B_\varphi = -\sum_{j=1}^{\infty} C_n \frac{\partial}{\partial\rho} I_n(a\rho)\cos n\varphi; \quad B_z = C\left(\frac{\partial I_1(a\rho)}{\partial\rho} + \frac{I_1(a\rho)}{\rho}\right), \quad (7)$$

and density of induced currents

$$j_\rho = 0\,;\; j_\varphi = -i\sigma\omega C I_1(a\rho);\; j_z = -i\sigma\omega\sum_{j=1}^{\infty} C_n I_n(a\rho)\cos n\varphi\,. \quad (8)$$

The dependences found make it possible to determine the average volume densities of electromagnetic forces causing the ingot or melt liquid phase motion during the interaction of the inductors electromagnetic field and the liquid metal in the skull or crucible furnace

$$f_\rho = \mathrm{Re}\left(j_\varphi B_z^* - j_z B_\varphi^*\right)/2\,; \quad f_\varphi = \mathrm{Re}\left(j_z B_\rho^*\right)/2\,;\; f_z = \mathrm{Re}\left(j_\varphi B_\rho^*\right)/2 \quad (9)$$

The distribution of the radial, azimuthal and axial components of the forces density will be analyzed for one version of the electromagnetic stirrer, which include $w_1 = 50$ turns azimuthally oriented winding with height $h = 0{,}5$ *м* and $w_2 = 5$ turns oriented in the plane $z0\rho$ at $\varphi_1 = \pi/6$. The effective current is $I = 500\,A$, and electrical conductivity, geometrical dimensions of the ingot and current frequency are S/m, $r = 0{,}06$ m, $r_1 = 0{,}07$ m, $r_2 = 0{,}08$ m, $f = 50$ Hz.

It has been ascertained that the density electrodynamic force component f_ρ achieve the highest value, which tends to compress liquid metal, and, in the case of the free surface presence, to form a positive meniscus of melt. The distribution of this force is almost uniform in azimuth, with the exception of zones adjacent to the winding with an axial orientation, which is understandable. The maximum value of the radial component of the force reaches at the boundary of the liquid metal and the solid phase of the metal or near the skull wall and for the values accepted in the calculation experiment, it turns out to be about 2500 N/m^3 with a smooth decrease to zero on the ingot axis. For component of electrodynamic force f_φ, the change in the direction of force action in azimuth becomes characteristic.

This force density magnitude is more than an order less than the radial magnitude. Obviously, the magnitude of this force density component will largely determine the nature of the motion of liquid metal. Wherein the expected motion of the liquid metal will be characterized by the formation of vortices in the azimuthal plane. And finally, the *z*-component of the force density f_z has an alternating character and its smallest value is half less than φ-component f_φ.

The presence of three electrodynamic force density components, although differing from each other by almost an order of magnitude or more, will lead to the appearance of a complex motion in the liquid metal, leading to its intense stirring. In the framework of the accepted calculation electrodynamic model, it is impossible to obtain the exact values of the quantities characterizing this movement. First of all, this is due to the adoption of the provision on the infinite height of the electromagnetic system, which leads to the absence of edge effects and problems associated with the free surface of the liquid metal.

In the work, on the basis of the obtained solutions on the distribution of the electromagnetic forces density, an assessment is made of the possible type of liquid metal motion.

The melt motion is described by the Navier-Stokes equation for an incompressible fluid in the approximation of laminar flows [9]

$$\frac{\partial u}{\partial t} + \left(u\; grad\right)u = -\frac{1}{\gamma} grad\; p + \nu\cdot\Delta u + \frac{f}{\gamma} \quad (10)$$

and the continuity equation

$$div\, u = 0\,.$$

In (10), the vector of the volume electromagnetic forces density f is determined by components (9); γ, ν are density and kinematic viscosity of liquid metal.

On the solid boundary of the melt ($\rho = r$) for a viscous fluid, from the sticking condition, the boundary condition is the equality

$$u_\rho = u_\varphi = u_z = 0\,. \quad (11)$$

In the approximation of a fixed slab, conditions (11) must also be satisfied when $\rho = 0$.

Due to the finite height of the electromagnetic stirrer, secondary metal flows arise commensurate with the velocities due to the action of electrodynamic forces (9).

Therefore, without pretending to an accurate quantitative description, we dwell only on the determination of characteristic flows, caused by the action of electromagnetic forces in the approximation of an infinitely high inductor. Given that within the framework of the assumptions made $\partial p / \partial z = 0$, excluding the influence of convective terms of the distribution, the components of the melt velocity are determined by the dependencies:

for ρ-component

$$\frac{\partial u}{\partial t} = \nu\left(\frac{\partial^2 u}{\partial \rho^2} + \frac{1}{\rho^2}\frac{\partial^2 u}{\partial \varphi^2} + \frac{1}{\rho}\frac{\partial u}{\partial \rho} - \frac{u}{\rho^2}\right) + \frac{f_\rho}{\gamma} \quad ,$$

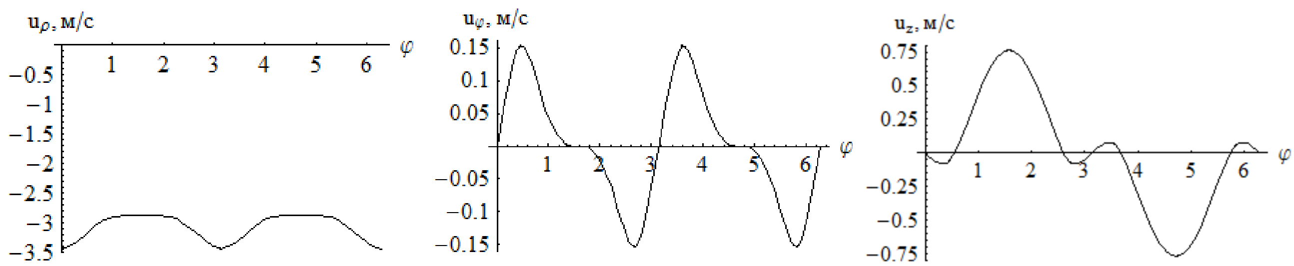
for φ -component

$$\frac{\partial u}{\partial t} = \nu\left(\frac{\partial^2 u}{\partial \rho^2} + \frac{1}{\rho^2}\frac{\partial^2 u}{\partial \varphi^2} + \frac{1}{\rho}\frac{\partial u}{\partial \rho} - \frac{u}{\rho^2}\right) + \frac{f_\varphi}{\gamma}, \qquad (12)$$

for z-component

$$\frac{\partial u}{\partial t} = \nu\left(\frac{\partial^2 u}{\partial \rho^2} + \frac{1}{\rho^2}\frac{\partial^2 u}{\partial \varphi^2} + \frac{1}{\rho}\frac{\partial u}{\partial \rho}\right) + \frac{f_z}{\gamma}.$$

The results of the numerical solution of equations (12) are presented in Fig. 2 as graphical dependencies after 10 seconds after the start of force action on the molten metal. In the calculations, it was assumed that the kinematic viscosity of the liquid metal is constant and equal to 2 10^{-7} S/m. The last assumption is very crude and can only be made for value judgments. The molten metal specific density is 7.8 10^3 kg/m^3. The figure 2 show the velocity distribution components along the azimuthal coordinate φ, radiant, and for value $\rho = 0{,}055$ m, i.e. at the interface of the solid skull substance and liquid phase metal.



a ***b*** ***c***

Fig. 2

For accepted constructive execution and current loads stirrer windings on the axis of symmetry of the inductor (z = 0), maximum value (3.5 m/s), as you can see from Fig. 2, reaches the radial velocity component u_ρ, somewhat lower values (0.75 m/s) takes axial component u_z and insignificant values (up to 0.15 m/s) reaches the azimuthal velocity component u_φ.

It can be seen from the figures that at the level of large radial velocities there are insignificant velocity inhomogeneities ∇u_ρ = 0.45 m/s, which together with the azimuthal velocity leads to the appearance of velocity vortices, the distribution of which is shown in Fig. 3, that contributes to the additional metal's stirring.

The above there is analysis of the local electromagnetic and dynamic characteristics of the electromagnetic system in the interaction with liquid metal. However, the above version of the electromagnetic system can be successfully used for induction melting of metal, for which an important characteristic is power consumption and energy efficiency. The resulting solution allows us to determine these energy characteristics. So, as applied to induction melting in crucible furnaces for which the main task is the maximum contribution of power for heating and melting the metal, the total power of the cylindrical inductor is

$$S_1 = \frac{\pi}{2} i\,\omega r_2^2\, h\,\mu (I w_1)^2 \left(1 + \frac{r_1^2}{r_2^2} \cdot M\right), \qquad (13)$$

and the power of the inductor of the orthogonal field is

$$S_2 = i\omega\pi r_2^2 h (I w_2)^2 \mu \frac{8}{\pi^2} \sum_1^n \frac{\sin(n\varphi_1)}{n^3}(1-2N), \quad (14)$$

where

$$M = \frac{I_1(a_1 r_1) - r_1 \frac{\partial}{\partial r_1} I_1(a_1 r_1) - B(K_1(a_1 r_1) - r_1 \frac{\partial}{\partial r_1} K_1(a_1 r_1))}{I_1(a_1 r_1) + r_1 \frac{\partial}{\partial r_1} I_1(a_1 r_1) - B(K_1(a_1 r_1) + r_1 \frac{\partial}{\partial r_1} K_1(a_1 r_1))},$$

$$N = n I_n\left(a_1 r_1\right) + r_1 \frac{\partial}{\partial r_1} I_n\left(a_1 r_1\right) - B_n\left(n K_n\left(a_1 r_1\right) + r_1 \frac{\partial}{\partial r_1} K_n\left(a_1 r_1\right)\right) /$$

$$\left(n I_n\left(a_1 r_1\right)\left(1 - \frac{r_1^{2n}}{r_2^{2n}}\right) + r_1\left(1 + \frac{r_1^{2n}}{r_2^{2n}}\right) \frac{\partial}{\partial r_1} I_n\left(a_1 r_1\right) - B_n(n K_n\left(a_1 r_1\right)\left(1 - \frac{r_1^{2n}}{r_2^{2n}}\right) + r_1\left(1 + \frac{r_1^{2n}}{r_2^{2n}}\right) \frac{\partial}{\partial r_1} K_n\left(a_1 r_1\right)\right).$$

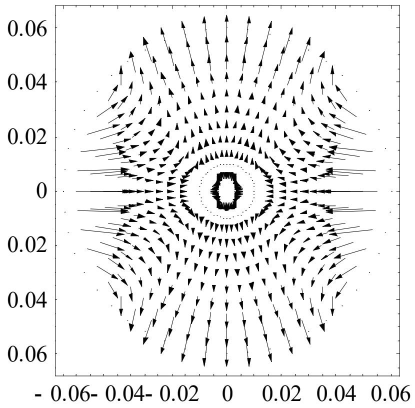


Fig. 3

The active power loss in the windings of both inductors is

$$P = \frac{I^2}{\sigma_o s_o}(w_1 \pi r_2 + w_2 (h + \pi r_2)),$$

where σ_0, s_0 are specific electrical conductivity and section inductor conductor windings.

The power calculations performed for the given stirrer parameters for the production of a continuously cast ingot with a diameter of 0.14 m show: at the industrial frequency the indicated metal stirring velocity is achieved when the power consumption from the network is $S_1 = 203 + 1150i$ VA, $S_2 = 2{,}9 + 9{,}1i$ VA, $P = 2856$ W at $s_0 = 39$ mm^2 and $\sigma_0 = 5 \cdot 10^7$ S/m. Supply voltage windings in this case is $U = \sqrt{2}\left(\left|S_1 + S_2 + P\right|\right)/I = 9$ V. It should be noted that insignificant power is consumed to perform the stirring functions – only about 206 W. Active losses in the winding are much larger, which leads to a low efficiency of the electromagnetic device. However, taking into account the functional purpose of such stirring, namely the stirring of liquid metal at the final stage of a continuously cast ingot production to improve its quality, the power of such an electromagnetic stirrer and its efficiency are offset by the achievement of the necessary modes of metal motion.

Conclusions. As a result of the electromagnetic and hydrodynamic processes analysis in an electromagnetic stirrer with orthogonal magnetic fields, it was ascertained that the radial velocity component has inhomogeneities along the azimuthal axis, leading to the formation of four additional vortices in the liquid metal. Such vortices work towards the intensification of the melt stirring process and can be used for electromagnetic stirrers of various functional purposes, namely: in the final stirrers of continuous casting machines, in crucible and skull furnaces.

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ЭЛЕКТРОМАГНИТНОЕ ПЕРЕМЕШИВАНИЕ МЕТАЛЛОВ В ПРОСТРАНСТВЕННО ОРТОГОНАЛЬНЫХ МАГНИТНЫХ ПОЛЯХ

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Разработана математическая модель и метод расчета параметров электромагнитной системы с пространственно ортогональными магнитными полями, которые создаются токами двух обмоток, одна из которых выполнена в виде цилиндрического индуктора, а вторая – в виде седлообразной катушки с линейными участками, направленными вдоль образующей индуктора. Определены средние объемные плотности электромагнитных сил, вызывающих движение расплава в процессе индукционного нагрева в тигельных печах или машинах непрерывного литья заготовок стали. Установлено, что на уровне больших радиальных скоростей имеют место незначительные неоднородности скорости, что совместно с азимутальной скоростью приводит к возникновению вихрей скорости и способствует дополнительному перемешиванию металла. Определено напряжение питания обмоток рассмотренного электромагнитного устройства, обеспечивающего перемешивание жидкого металла на финальной стадии производства непрерывнолитого слитка. Библ. 9, рис. 3.
Ключевые слова: расплавленный металл, электромагнитное перемешивание, электромагнитная сила.

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ЕЛЕКТРОМАГНІТНЕ ПЕРЕМІШУВАННЯ МЕТАЛІВ У ПРОСТОРОВО ОРТОГОНАЛЬНИХ МАГНІТНИХ ПОЛЯХ

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Розроблено математичну модель і метод розрахунку параметрів електромагнітної системи з просторово ортогональними магнітними полями, які створюються струмами двох обмоток, одна з яких виконана у вигляді циліндричного індуктора, а друга – у вигляді сідловидної котушки з лінійними ділянками, які спрямовані вздовж твірної індуктора. Визначено середні об'ємні щільності електромагнітних сил, що викликають рух розплаву в процесі індукційного нагріву в тигельних печах або машинах безперервного лиття заготовок сталі. Встановлено, що на рівні великих радіальних швидкостей мають місце незначні неоднорідності швидкості, що спільно з азимутальною швидкістю призводить до виникнення вихорів швидкості і сприяє додатковому перемішуванню металу. Визначено напругу живлення обмоток розглянутого електромагнітного пристрою, що забезпечує перемішування рідкого металу на фінальній стадії виробництва безперервнолитого злитка. Бібл. 9, рис. 3.
Ключові слова: розплавлений метал, електромагнітне перемішування, електромагнітна сила.

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