ЭНЕРГЕТИКА

EVALUATION OF DEPTH OF PENETRATION OF ELECTROMAGNETIC WAVE IN MELTED ALUMINUM

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ОЦЕНКА ГЛУБИНЫ ПРОНИКНОВЕНИЯ ЭЛЕКТРОМАГНИТНОЙ ВОЛНЫ В РАСПЛАВЛЕННЫЙ АЛЮМИНИЙ

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Abstract

Induction machines of small size are used in the modules for pumping molten metal, called electromagnetic trays. Such devices are created according to the technical task of the metallurgical enterprise using engineering methods of calculation. To improve the traction characteristics, a flat or cylindrical magnetic circuit is used. However, for induction machines with an open magnetic core, the asymmetry of the electromagnetic regime is characteristic, which is difficult to take into account in the preliminary calculation. Therefore, to clarify the regime parameters and preliminary evaluation of the efficiency of longitudinal field inducers, engineers perform numerical simulation of the magnetic, hydrodynamic and thermal field of the tray on a computer. One of the most important characteristics of the inductor can be considered the depth of penetration of the traveling magnetic field into the molten metal.

Keywords

The running magnetic field, electromagnetic tray, longitudinal magnetic field inductor, plane electromagnetic wave, wave penetration depth into metal, hydrodynamics of aluminum melt, electromagnetic pump, mathematical simulation.

Аннотация

Индукционные машины малого габарита применяют в составе модулей для перекачивания расплавленного металла, называемых электромагнитными лотками. Такие устройства создают согласно техническому заданию металлургического предприятия с применением инженерных методик расчёта. Для улучшения тяговых характеристик используют плоский или цилиндрический магнитопровод. Однако для индукционных машин с разомкнутым магнитопроводом характерна несимметрия электромагнитного режима, которую трудно учесть в предварительном расчёте. Поэтому для уточнения режимных параметров и предварительной оценки эффективности индукторов продольного поля выполняют численное моделирование магнитного, гидродинамического и теплового поля лотка на ЭВМ. Одной из важнейших характеристик индуктора можно считать глубину проникновения бегущего магнитного поля в расплавленный металл.

Ключевые слова

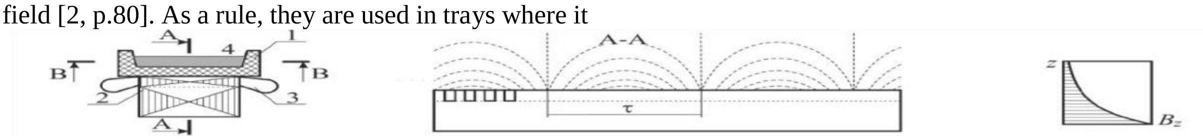
Бегущее магнитное поле, электромагнитный лоток, индуктор продольного магнитного поля, плоская электромагнитная волна, глубина проникновения волн в металл, гидродинамика алюминиевого расплава, электромагнитный насос, математическое моделирование

Formulation of the problem. The use of electromagnetic devices for pumping molten aluminum can overcome the shortcomings of mechanical pumps [1, p.24]. Unlike mechanical devices, electromagnetic inductors of the longitudinal magnetic field exclude direct contact with the melt, provide high accuracy and flexibility of control [2, p.45]. One of the most suitable devices for moving melts is the electromagnetic tray. However, the efficiency of the tray largely depends on the depth of penetration of the magnetic field into the aluminum. In the study of metallurgical equipment, numerical modeling tools are used. However, the preliminary evaluation is carried out according to analytical expressions [3, p.28]. For induction machines of small dimensions, known analytical expressions give large errors [4, p.122]. Using mathematical modeling tools, the formula for determining the depth of penetration of an electromagnetic wave of a running magnetic field can be clarified.

Metallurgical enterprises are equipped with melting and casting units, which operate on a two-stage or single-stage process diagrams. Melting and casting units can differ in the types of furnaces, arrangement of equipment, features of the technological cycle [1, p.12]. A common feature is the need to pump the melt from the furnace to the furnace or from the furnace to the crystallizer, and various devices are used for this. Strict requirements for pumping melt remain unchanged, therefore mechanical pumps are considered morally obsolete. Among many machines for pumping aluminum between furnaces, one can distinguish a group of flat and cylindrical inductors of a longitudinal magnetic field [2, p.80]. As a rule, they are used in trays where it is not necessary to create powerful devices with a large depth of electromagnetic wave penetration. This condition corresponds to shortened induction machines with a ferromagnetic secondary element. A feature of multiphase machines can be considered their short-pole and low-frequency structure [5, p.62].

A sketch of the construction of a flat electromagnetic tray is shown in Figure 1, a. The tray consists of a channel (1), a magnetic circuit (2), in whose slots a multiphase winding (3) is located. The induction machine is placed under the molten metal (4). The side of the inductor, directly below the channel, is called the working one. The distance from the surface of the inductor to the melt is usually called the working gap. The larger the value of the working gap, the less the magnetic field penetrates into the melt. Conditionally believe that the inductor is an analog of the deployed stator of the induction motor (Figure 1, b), on the surface of which a running magnetic field is created [4, p.37].

The amplitude of magnetic induction B_z over the active zone of the inductor varies exponentially (Fig. 1, c). The intensity of the damping depends on the magnitude of the pole pitch, by which is meant the distance occupied by each of the inductor poles. The distance along the inductor, at which the phase changes by 2π, is the period of the spatial structure of the winding. At this distance 2τ there are two magnetic poles. As the step of pole increases, the length of the phase zones increases proportionally. In addition to flat inductors, in practice, multiphase induction machines with a cylindrical magnetic core and disk coils placed around the core are used [5, p.64].



a b c

Figure 1

The magnetic flux lines crossing the melt induce eddy currents in it (Fig. 2, b). The interaction of the traveling magnetic field and eddy currents creates volumetric electromagnetic forces that cause the melt to move (Figure 2, a). With an increase in any of the parameters (□, □, *f*) , the increase in force goes to the maximum region. But further it is seen that the force decreases and tends to zero [3, p.70] . The diagram of the distribution of tractive effort is shown in Figure 2, c.

a b c

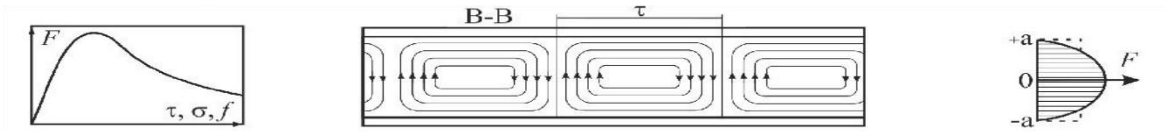


Figure 2

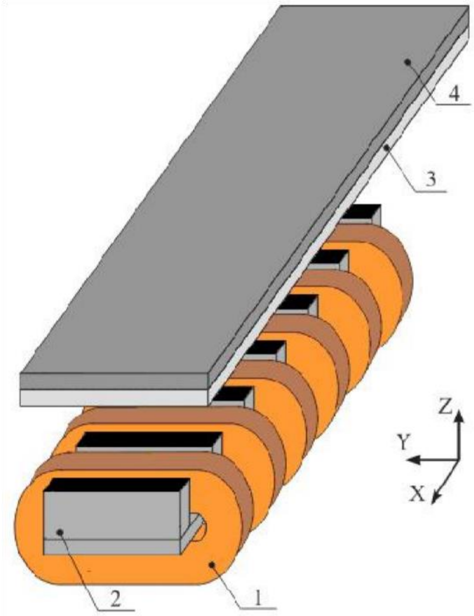
The improvement of numerical methods and analysis tools led to a radical change in the situation when using numerical models of complex technical systems. Numerical methods have obtained decisive advantages due to the evolution of computer technology, software and rapid increase in processing power. The input languages of modern software are highly developed, the user interface is improved. This made it possible to simplify the construction of numerical models, up to semi-automatic algorithms for their generation. On the basis of models, an iterative numerical solution of the field equations is organized [1, p.111] . Software tools for modeling induction machine regimes are used at the stage of analysis of the first technical solutions obtained, often in comparison with the results of a physical experiment.

Two-dimensional numerical models give a satisfactory agreement with experiment for axisymmetric systems with a traveling magnetic field. For planar systems, the quantitative errors in the calculation of two-dimensional problems can be excessive, and often lead to a qualitatively different result. This is due to difficulties in describing in the two-dimensional model the specific elements of the system, for example, the outer parts of the windings and their mutual arrangement. Accounting in the two-dimensional formulation of edge effects in the melt is also problematic.

The induction machine for the electromagnetic tray is a complex technical system built by solving interrelated problems in electrical circuits, electromagnetic, magnetohydrodynamic and heat fields. The study of heterogeneous objects of high complexity should be carried out in a complex manner, taking into account the most significant factors and their interrelationships. In the "inductor-channel" system, this is the mutual influence of magnetic and hydrodynamic fields on each other. Their ratio forms the dynamics of the displacement of the aluminum melt in the channel and the distribution of the resultant electromagnetic field of the inductor. The results of application of both 2D and 3D models are presented in the literature [1, p.123].

As a rule, the results of the calculation in a three-dimensional formulation better coincide with the results of the experiment. However, it was not possible to find a system assessment of the question of the quality of docking of two-dimensional and three-dimensional models in metallurgical problems. Apparently, there is no quantitative assessment of the reliability and comparison of the accuracy of such calculations for large-dimensional problems. Therefore, it was not possible to establish recommendations on the limits of the use of models. A sketch of the computational domain in the model intended for the analysis of the electromagnetic field in the "inductor-channel" system is shown in Fig. 3.

The working area of the "inductor" of the electromagnetic tray is called a flat electromagnetic system. And in the investigated object it is necessary to accurately estimate the nature of the moving magnetic field. It is known that truncated induction machines are characterized by the presence of edge effects (longitudinal, transverse, input and output). Therefore, it is important to compare three-dimensional and twodimensional models and assess the degree of coincidence of the results.



The problem is that when taking into account the design features of the inductor, the calculation time can be excessive. Therefore, in the construction of the model, a number of Figure 3 assumptions and limitatithe assumptions made should ons are introduced, but not distort the real picture of the field. It should be noted that

three-dimensional problems require substantial computing resources. Duration of calculations on cluster computers can be hundreds of hours. At the same time, sometimes, for making a decision, it is necessary to quickly evaluate the effect of design parameters on the device mode. The question of comparing models is relevant, since the system under investigation can have several design options. Therefore, to make a decision, it is necessary to ensure minimum requirements for computational resources.

The problem of analyzing the field must be solved in the system of Maxwell's equations. For simplicity, the known method is used and a universal variable is introduced, the vector potential of the magnetic field $\bar{A}$. The use of $\bar{A}$ excludes unknowns from the system, allowing one to obtain an equation of one variable.

$$\bar{j} = -\gamma \cdot \frac{\partial}{\partial t} - \gamma \left[\bar{V} \cdot rot\ \bar{A} \right], \qquad (1)$$

At the initial stage, the currents of the induction unit are assumed to be sinusoidal. Therefore, the field in the working region can be considered harmonic in accordance with (1), and the regime parameters are represented in a complex form. By the equations of a quasistationary field, one proceeds to a simplified, flat twodimensional or three-dimensional formulation. The magnetic induction vector is considered to be located in the plane of the tray, while the vector of the electric current density J and the vector magnetic potential A are orthogonal to it. In the twodimensional formulation, the components Jy and Ay are nonzero, and in the threedimensional formulation there are all components.

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_y}\frac{\partial \dot{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu_x}\frac{\partial \dot{A}}{\partial y}\right)-i\omega\gamma\cdot\dot{A}=-j_{cm}, \quad (2)$$

$$\frac{\partial}{\partial x}\left(\frac{1}{\mu_y}\frac{\partial \dot{A}}{\partial x}\right)+\frac{\partial}{\partial y}\left(\frac{1}{\mu_x}\frac{\partial \dot{A}}{\partial y}\right)+\frac{\partial}{\partial z}\left(\frac{1}{\mu_z}\frac{\partial \dot{A}}{\partial z}\right)-i\omega\gamma\cdot\dot{A}=-j_{cm}, \quad (3)$$

The solution of the field equations (2, 3) is a boundary value problem. For its correct description, boundary conditions are applied and the equations are solved together with the boundary conditions. Next, the traction characteristics of the electromagnetic field are calculated. For this, engineers usually use specialized software environments [5, p.66].

Calculation of the electromagnetic field in the working region is performed by the finite element method. For this, the software Ansys Multiphysics is used. When building models, the programming language APDL was used. Conversion of input and output information flows is performed in ASCII code, which is beneficial from the point of view of the formation of hybrid models. At the same time, integration of third-party calculation models with external software modules is performed. In addition, the ASCII code is convenient for processing the calculation results. The models described here are formalized in the format of internal program code and additional modules - macros. Macros act as docking nodes for heterogeneous tasks, and also carry service options to support the execution of non-standard functions [1, p.55].

At the first stage, to accept the decision on the model, the launch regime was investigated. The electromagnetic force in the starting mode determines the starting pulse necessary to start the melt movement. The intensity of metal movement depends on a large number of criteria. These include linear current load, frequency, working gap, pole division, melt parameters, magnetic circuit characteristics, etc. Approximately 50 criteria are adopted. Identifying the most significant dependencies and their formalization requires a large number of calculations and leads to optimization problems. Consequently, already at this stage the question of the applicability and adequacy of two-dimensional or three-dimensional models becomes relevant.

In the study, two parametric models of the "inductor-channel" system were developed and tested: in two-dimensional and three-dimensional formulations. To compare the calculation results, the geometry parameters and the power supply mode of the model are set to the same. Some results are shown in Fig. 4.

The regulation of the supply voltage frequency has shown that the tangential force Fτ has a characteristic optimum. And for the two-dimensional case (curve 1), the optimum is located at a frequency of 3 Hz, and for a three-dimensional (curve 2) at 17 Hz. The difference in effort values is 53 %. In addition, the behavior of the curves is significantly different. The nature of the region of optimal values along curve 1 looks relatively high-quality.

Curve 2, on the other hand, shows a low selective extremum. At a frequency of 23 Hz, the curves intersect, and further curve 1 is located below curve 2 (~ 7 %). Thus, the results of calculating the electromagnetic force by the twodimensional and three-dimensional models are different.

Further studies showed a different character of the distribution of the amplitude value of the magnetic induction in the melt at frequencies below 12 Hz. The induction

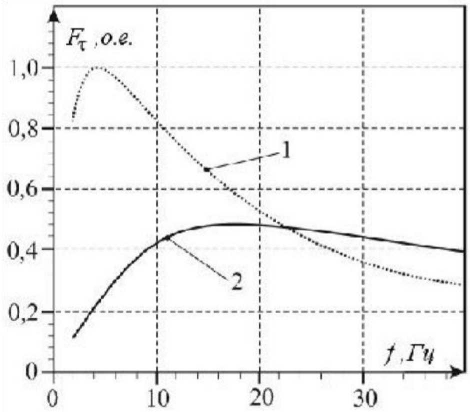


Figure 4

distribution for the three-dimensional model is more uniform along the length of the channel of

the melt and has no characteristic dips. The two-dimensional model is characterized by too high induction values (up to 76 %). This explains the higher calculated values of the forces in Fig. 4, but does not explain the change in the nature of their distribution.

The presence of previously developed prototypes of induction machines facilitates the task of comparing the results of numerical simulation. Despite the fact that the samples of longitudinal field inducers were manufactured without the use of optimization algorithms, the main regularities of the force effect for the threedimensional models were basically confirmed. To power physical samples, a transistor IGBT converter with a capacity of 50 kVA was used, and the devices themselves were mounted on an experimental bench.

The two-dimensional model allows to take into account the input and output edge effects (x-axis). But does not take into account the transverse effect associated with a change in the direction of the vortex current vector by 90 °, along the lateral surface of the channel. In addition, due to the presence of frontal parts of winding, there is a distortion of the distribution of the magnetic field within the active part of the inductor (y axis). Therefore, two-dimensional numerical models for the analysis inductors of short-pole linear induction machines in such a formulation should not be used. For the adoption of technical and economic solutions, it is necessary to form a full-fledged three-dimensional numerical model at the stage of preliminary calculations and to calculate the mode parameters, taking into account the most important factors determining the device's efficiency.

To quantify the limit values of the starting angles of the electromagnetic tray, a thorough study of the set of criteria, the construction of a detailed model, and the refinement of the research algorithm are required. In addition, a large amount of computation and a system analysis of the results are required. Therefore, the study of the launch regime is allocated to a separate project.

In the theory of induction machines, the concept of the depth of penetration of the magnetic field into the melt is used. If the thickness of the metal is much greater than , then in the most remote layers of the melt, backflows can occur and condition

(1) will not be fulfilled. Therefore, take the condition $h_k = 1.41$, at which the optimum mode of operation of the inductor takes place. According to the literature, the penetration depth □ is determined by the expression:

$$\delta = 503 / \sqrt{\sigma \cdot \mu \cdot f}\,. \quad (4)$$

The calculation results from expression (4) showed a significant difference from the values described above. For 1.41 □ = 50 mm, the frequency is f = 40 Hz. But with a decrease in thickness, the dependence is shifted to the range of kilohertz. Consequently, the use of classical expressions does not accurately describe the electromagnetic mode of the induction machine.

The study [1, p.76] shows an expression that clarifies this discrepancy. The justification is the indication of the evaluation of the results for a plane electromagnetic wave (3). The concept of a plane wave assumes that. This assumption is inapplicable for a real short-pole inductor. Therefore, the calculated values of penetration depth differ significantly from those measured. For their correct definition, the following expression is used:

$$\delta = \sqrt{\frac{2}{\sqrt{[(\pi/\tau)^4 + (2\pi \cdot \sigma \cdot f \cdot \mu)^2]} + (\pi/\tau)^2}}\,. \quad (5)$$

The structure of expression (5) indicates that the depth of penetration depends not only on the conductivity , the frequency *f* of the supply voltage, but also on the magnitude of the pole division . However, analysis of the results of numerical simulation showed that the calculated values of the frequencies also significantly exceed the results obtained from expression (4). A detailed quantitative evaluation shows the unsuitability of the analytical expression (5) for determining the penetration depth of the wave developed by the inductor of the electromagnetic tray. Studies have shown that taking into account the non-magnetic gap Δ leads to a sharp change in the location of the optimal regime characteristics, whose behavior is shown in Fig. 6. This shows the necessity of taking into account the influence of Δ in expression (5). To refine the analytical expression (5), a series of approximation procedures is performed, using splines. As a result, we obtained a refined expression for estimating the penetration depth of an electromagnetic wave, which makes it possible to reliably describe the result.

$$\delta = (1 + k\xi) \cdot \sqrt{\frac{2}{\sqrt{[(\xi / \Delta)^4 + (2\pi f \cdot \sigma \cdot \mu)^{(2+\xi)}]} + (\xi / \Delta)^2}}\,, \quad (6)$$

where ξ □ π □ □ / τ, is the correction factor of the penetration efficiency of the running electromagnetic wave through the non-magnetic gap; k = 1 ÷ 2 - the coefficient of influence of the secondary element on the penetration depth of the electromagnetic wave.

The obtained analytical expression (5) shows the corrected regularity of the distribution of values of the penetration depth of the wave, for the considered class of electromagnetic trays. The formula makes it possible to calculate the penetration depth at a given frequency, taking into account the joint influence of the essential technological parameters of the "inductor-channel" system. The product of the newly introduced coefficients ξ and *k* in the formula (5) integrally takes into account the effect of the physical parameters of the device and the geometric characteristics of the short-pole machine. For the considered design designs, with the secondary element and without it, on the basis of multivariate numerical studies the values of the coefficient *k* = 1 ,2 and 1,8, respectively, were adopted.

Comparison of calculation results by analytical expression and results of numerical simulation confirmed the high degree of coincidence of not only discrete values, but also accurate reproduction of the monotonous regularity of distribution of optimal values of f_{opt} and $h_к$ for the system under study. In addition, a comparison of the results of the calculation of the regime characteristics with the results of a physical experiment on the trays from a number of designed products. Comparison showed an acceptable quality of coincidence. Therefore, the need for preliminary numerical simulation with long and resource-intensive iterative calculations has been exhausted.

The dependence of the optimal tangential force $F_τ$ on the melt height h_k for the case with the secondary element (2) and without it (1) is shown in Fig. 5. Dependences of the optimal frequencies f_{opt} on the melt height h_k for the case with the secondary element (2) and without it (1) is shown in Figure 6. The behavior of the regime parameters of the induction machine is important to evaluate when searching for the optimum frequency. Automated search of optimal values of frequency f_{opt}, allowed to conclude that all dependences are essentially nonlinear (Figure 5). An increase in h_k leads to an exponential decrease in the frequency. And for both constructive options the behavior is the same. The displacement of the curves is 26 % in practically the entire range.

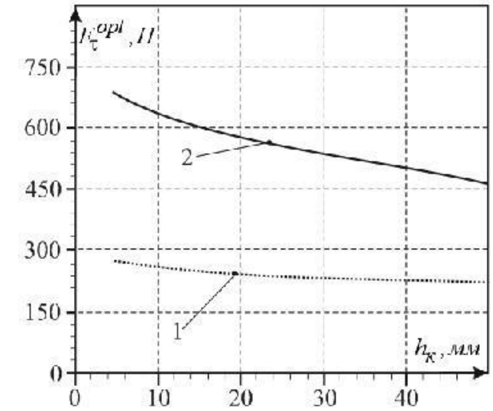


Figure 5

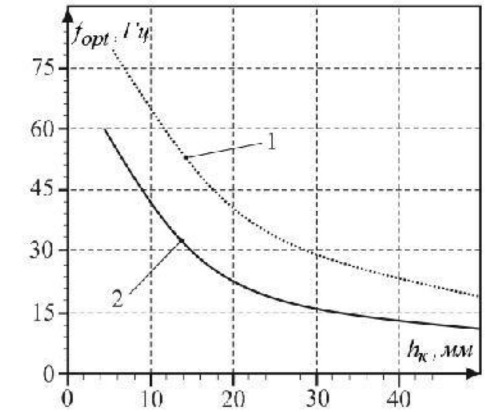


Figure 6

Based on the results of the study, engineers can formulate generalized recommendations for constructing an effective tray design. At the same time, it is possible to take into account a combination of technological, energy, constructive and cost factors. In particular, an inductor with a magnetic core of circular cross section is proposed. It makes it possible to simplify the design, facilitate the device, improve cooling conditions, and also solve the problem of parametric synthesis of operating modes in a simplified formulation.

For an inductor with an ascending channel, the first criterion of the efficiency of work is the minimum starting level of the melt. The determining factor is the traction force F in the channel. The value determined from the condition for balancing the hydrostatic pressure force. It should be noted that, for pressure electromagnetic trays, the starting level of the melt is critical only at the launch stage. For non-pressure trays, it is important throughout the entire process. The inductor of the electromagnetic tray has an uneven density of electromagnetic forces along the length of the channel. The lowest density is characteristic for the zones of the beginning and end of the inductor, and also beyond its limits. In the course of a numerical experiment, the integral power characteristics were estimated on the induction machine model for the tray. A characteristic feature of the constructed models is their greater dimensionality and high complexity, since the real geometry of the tray and the electrophysical characteristics of the induction machine are taken into account.

The study used a comparison of the two models of the electromagnetic tray, created for the pressure and non-pressure versions. The steady state is studied at different frequencies. The melt level in the channel is considered in the range from 0 (idle) to 1.2 m. The numerical experiment carried out confirmed the hypothesis of increased efficiency of the proposed inductor design of the electromagnetic tray with the ferromagnetic secondary element.

Conclusions. As a result of the development and research of parametric numerical models in the ANSYS software environment, it was possible to evaluate the differential characteristics of the electromagnetic field and to study the regularities of the occurrence of physical processes in the electromagnetic system of tray. In addition, in the study was received:

1. The integral characteristics of the field made it possible to evaluate the magnitude of the electromagnetic force and the energy efficiency of various inductor modifications in comparison with the proposed short-pole design.
2. Dependencies of the mode parameters of the low-pole inductor in the task of optimizing the tray modes, as well as practical recommendations for the operation of the device.

3. Modified dependence of the penetration depth of the magnetic field in the metal melt, taking into account additional factors: the magnitude of the non-magnetic gap, pole division and the secondary element.

References

1. Горемыкин, В.А. Численное и физическое моделирование электромагнитного лотка для транспортировки расплавов алюминия: дис. … канд. техн. наук:

05.09.01. – Красноярск: ИПЦ СФУ, 2015. – 176с.

2. Верте, Л. А. Электромагнитная разливка и обработка жидкого металла. – М.:

Металлургия, 1967. – 207 с.

3. Гельфгат, Ю. М. Жидкий металл под действием электромагнитных сил /

Ю. М. Гельфгат, О. А. Лиелаусис, Э. В. Щербинин. – Рига: Зинатне, 1976. – 251с.

4. Полищук, В. П. Магнитодинамические насосы для жидких металлов / В. П. Полищук, М. Р. Цин и др. – Киев: Наукова думка, 1989. – 257 с.

5. Tyapin, A.A. Inductors for electromagnetic stirrers // Znanstvena Misel Journal / Global Science Center LP, Lubljana, №19-1, 2018. – p. 64-67.