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INVESTIGATION OF THE PARAMETERS INFLUENCE OF A CYLINDRICAL INDUCTOR WITH TWO-LAYER INWALL ON ITS TEMPERATURE

Abstract. The thermal state of a cylindrical inductor with a two-layer inwall was investigated: the inwall temperature of the inductor for 12 pairs of heat-insulating materials of the inwall layers was calculated, and the influence of changes in the thicknesses of inner and outer inwall layers for fireclay-asbestos pair on the inwall temperature.
Key words: thermal calculation, induction heater, inwall, temperature, heat transfer, cylindrical workpiece.

Introduction. Heating of details in inductors at the expense of radiation energy is widely applied in many technological lines of the industry mainly due to the high heating rate and non-contact method of energy transfer. However, for efficient use of induction heaters it is necessary to increase the accuracy and reliability of their design, which is achieved by analysis characteristics of the thermal calculation of the system "heater-part", which must take into account the simultaneous action of several factors that significantly affect the process heating: change of thermophysical properties of the material of the workpiece depending on the temperature, the drop in its temperature due to energy consumption from surfaces, etc. [6].

Analysis of recent research and publications. Detailed review of research and calculations of thermal and magnetic processes in inductors up to 2011, as well as their impact on the optimization of the design and operation of inductors can be found in [5].

Optimization of the design and geometric dimensions of the inductor associated with heat loss and magnetic field, are devoted to [9, 13].

Thus, the authors in [13] describe the method of design and optimization for a small inductor; calculations are performed to minimize conductivity losses in winding by optimizing the volume of copper and the cross-sectional size of the conductor. The method combines analytical development with modeling using the finite elements method, providing a significant reduction in computing costs. Parametric analysis is performed to determine the optimally efficient induction system.

In [9], the optimization of the thermal heating of the inductor is investigated, which allows to reduce its size. The authors emphasize that complex forms are required inductor cores, and offer a specific methodology for determining the best form factor to optimize the exchange surface on the inductor.

The authors of [11] perform a numerical calculation of the temperature field in an aluminum inductor, which is confirmed by the results of physical experiments.

The purpose of the article [7] is to study the influence of geometric parameters, namely the number of layers and cross-section of the copper busbar and coils of the valve on the power and the speed of the inductor, which affects the temperature change of its components.

In [14] a simple and accurate method of designing inductors with a gap is proposed. The method is simple both in algorithm and in calculation, because it requires only a small number of iteration cycles. The authors demonstrate that the proposed method of calculation can easily include different models, which affect the design of the inductor, including thermal characteristics: temperature, flux density, heat loss.

The authors of [10] consider three-dimensional formulations of a mathematical model of the process of eddy current induction in ferromagnetic materials in order to calculate temperature fields of induction heating devices. Two calculation algorithms have been proposed that can significantly reduce computer consumption time with reasonable accuracy. Using the calculation of temperature fields in molds and vulcanized products as an example, the authors confirm the validity of the proposed approach.

When heated by electromagnetic induction, the shape of the coil and the air gap between the inductor and the workpiece can affect the distribution of the heat source. At work [8] used the finite element method to calculate the distribution of heat sources by different initial parameters of the coil. As a result, changes were investigated heat source distribution.

In [12], the effect of eddy currents of superconducting magnets on the resulting ohmic heating was investigated, which is an undesirable effect because it changes the operating magnet temperature. Numerical simulation of these eddy currents is important to compensate for the control of their adverse effects.

Thus, a review of recent studies shows that the thermal calculation of the inductor as a whole and the determination of the thermal state of its individual layers – very an urgent problem that can be used in the problems of optimizing its design and functioning processes.

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The purpose of the study: to establish the effect of changes in the thickness of the outer and inner layers of the two-layer inwall, as well as thermal insulation materials on the temperature inwall of a cylindrical inductor for heating a metal workpiece.

Presentation of the main material of the study. The mathematical model of a cylindrical induction heating system includes three equations in partial derivatives for cylindrical workpiece (1), inwall (2) and magnetic system of inductor (3), respectively [5]:

$$\frac{\partial T_1(r,\theta,x,\tau)}{\partial\tau} = a(T_1)\left[\frac{\partial^2 T_1(r,\theta,x,\tau)}{\partial r^2} + \frac{1}{r}\frac{\partial T_1(r,\theta,x,\tau)}{\partial r} + \frac{\partial^2 T_1(r,\theta,x,\tau)}{\partial x^2}\right] +$$

$$+ a(T_1)\frac{1}{r^2}\frac{\partial^2 T_1(r,\theta,x,\tau)}{\partial\theta^2} + \frac{1}{c(T_1)\gamma(T_1)}W(r,\theta,x,\tau),\ r\in(0,R_1),\ x\in(0,L), \quad (1)$$

$$\frac{\partial T_2(r,x,\tau)}{\partial\tau} = a_2(T_2)\left[\frac{\partial^2 T_2(r,x,\tau)}{\partial r^2} + \frac{1}{r}\frac{\partial T_2(r,x,\tau)}{\partial r} + \frac{\partial^2 T_2(r,x,\tau)}{\partial x^2}\right],\ r\in[R_2,R_3], \quad (2)$$

$$\frac{\partial T_3(r,x,\theta,\tau)}{\partial\tau} = a_3(T_3)\left[\frac{\partial^2 T_3(r,x,\theta,\tau)}{\partial r^2} + \frac{1}{r}\frac{\partial T_3(r,x,\theta,\tau)}{\partial r} + \frac{\partial^2 T_3(r,x,\theta,\tau)}{\partial x^2} +\right.$$

$$\left.+\frac{1}{r^2}\frac{\partial^2 T_3(r,x,\theta,\tau)}{\partial\theta^2}\right] + \frac{1}{c_2(T)\gamma_2}Q_1(\theta,\tau),\ r\in[R_3,R_4], \quad (3)$$

where R_1, R_2, R_3, R_4 – radii of the workpiece surface, the inner surface of the inwall, the interface of the inwall and the inductor, as well as the outer surface the magnetic wire of the inductor, respectively;

$W(r,\theta,x,\tau)$ – the internal heat source of the workpiece;

$Q_1(\theta,\tau)$ – the function of the heat source of the inductor;

c, c_2, γ, γ_2 – heat capacity and specific the electrical conductivity of the workpiece and the inductor, respectively.

Unambiguous solution of the system (1-3) is possible by setting boundary conditions that involve determining the thermal regime on the side surface of the cylindrical workpiece, on its end surfaces, on the end surfaces of the inwall, on the outer surface of the magnetic wire and on its ends, as well as the task of ideal thermal contact between the surfaces of the inductor and the outer surface of the inwall [5].

This system is further complicated when the inwall has two layers, so to solve the problem, the approach was used, proposed in [6], which is based on solving the equation of heat balance between the workpiece and the inwall of the inductor.

The design scheme of a cylindrical inductor with two layers of inwall is shown in Fig. 1.

The calculations were performed according to the following data:

– the temperature of the outer surface of the workpiece $T_S = 1250^0$ Ñ;

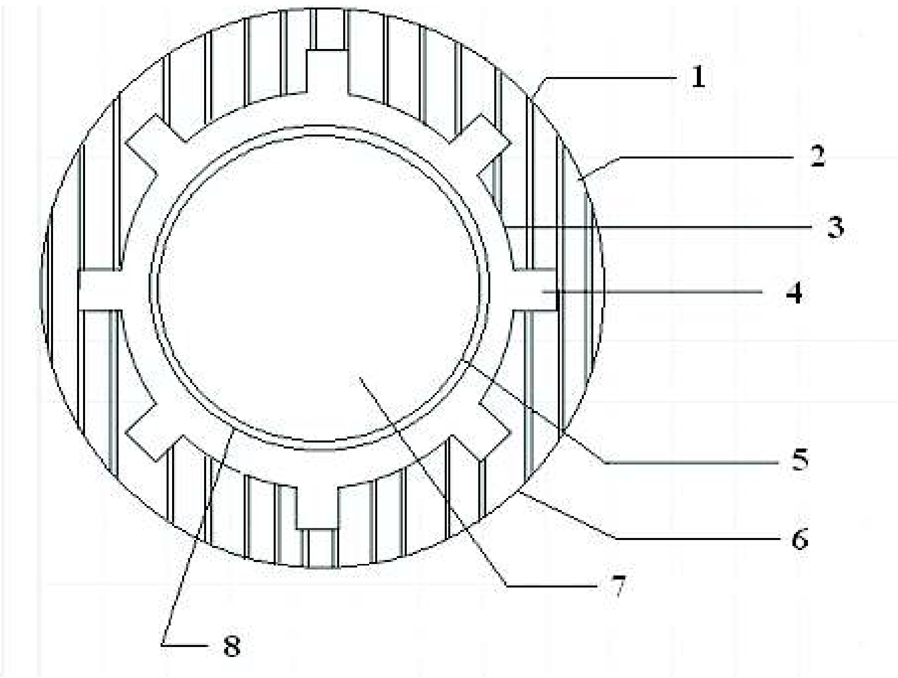
– the temperature of the outer surface of the inwall adjacent to the winding inductor $T_{IN} = 30^0$ Ñ;

– the outer diameter of the outer (first) layer of the inwall $d_3 = 0{,}074$ ì ;

– the inner diameter of the outer (first) layer of the inwall $d_2 = 0{,}07$ ì ;

– inner diameter inner (second) layer of inwall $d_1 = 0{,}045$ ì ;

– radius of cylindrical workpiece $R = 0{,}02$ ì .



1 – inductor magnetode wire; 2 – insulation;
3 – outer diameter d_3 of the first layer of the inwall;
4 – winding (coil) of the inductor;
5 – inner diameter d_1 of the second layer of the inwall;
6 – inductor; 7 – medium for heating the workpiece;
8 – outer diameter d_2 of the second layer of the inwall

Figura 1 - Scheme of a cylindrical inductor

In the table 1 presents pairs of materials of the inwall layers used in the calculations and their thermal conductivity coefficients [1, 3-4]. Insulators are selected as

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follows in such a way that starting from the pair № 2, the thermal conductivity of the material of each layer of the inwall increases.

Fig. 2 represents the change in the temperature of the inwall on the inner surface of the second layer depending on the selected pair of materials of the inwall layers of table 1. The presented diagram allows to obtain quantitative values of the inwall temperature for a cylindrical inductor with selected characteristics and confirms quality-expected result: the desired highest temperature can be achieved by using materials with lower thermal conductivity.

Table 1

Numbering of materials of inwall layers
and their thermal conductivity coefficients λ_I, $W/(m \cdot \hat{E})$

Inwall layers	**1**	**2**	**3**	**4**	**5**	**6**
internal	chamotte, 1,33	gravel, 0,93	grit, 0,97	fire-resistant brick, 1,05	faience, 1,15	cement-grit, 1,2
external	asbestos, 0,175	min. cotton wool, 0,045	fiberglass, 0,05	siliceous plates, 0,07	vermi-culite, 0,1	granulated slag, 0,15
Inwall layers	**7**	**8**	**9**	**10**	**11**	**12**
internal	porous concrete, 1,4	gritstone, 1,5	limestone, 1,7	asbestos cement, 1,76	cement slabs, 1,92	quartz glass, 2,1
external	slag wool, 0,167	glassine, 0,17	thermoiz. concrete, 0,18	expanded clay conc-rete, 0,2	bakelite, 0,23	teflon, 0,25

In the second stage of research, the first pair of "chamotte-asbestos" was selected as heat-insulating materials of the inwall layers of the cylindrical inductor in order to establishing the effect of changes in the thickness of the inwall layers on its temperature. The result is presented in Fig. 3.

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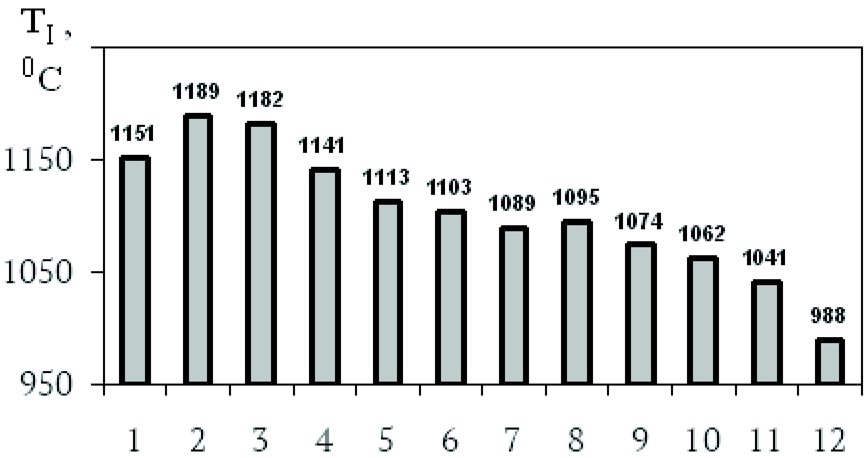
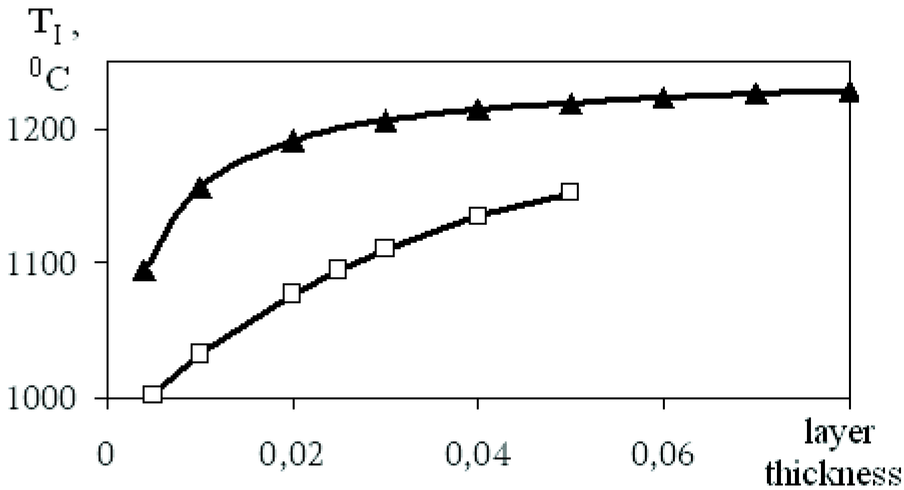


Figura 2 - The temperature of the inner surface of the inwall depending on the pair of materials of its layers



– asbestos layer (outer);

– chamotte layer (inner)

Figura 3 - The dependence of the temperature of the inwall on the thickness of its layers

Analysis of fig. 3. shows that the change in the thickness of the inner layer of chamotte has a much stronger effect on the change in temperature than the change in the thickness of the outer layer of asbestos. In addition, the graph shows that it is impractical to increase the thickness of the outer layer of asbestos more than 0.02 m – this does not lead to a significant change temperature.

The presented results were tested at the XXI International Conference "Human and Space" [2].

Conclusions. In the course of performance of the set task the following types of works were carried out and conclusions were received:

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1) the algorithm for calculating the inwall temperature of the electric inductor depending on the thickness of the outer and inner layers, and also depending on the heat-insulating inwall material was created;

2) the testing of the created algorithm on the problem of this class with a known solution obtained by Pavlov in [6] was performed;

3) the inwall temperature of the electric inductor for the following materials: chamotte-asbestos, gravel-mineral cotton wool, grit-fiberglass, fire-resistant brick-siliceous plates, faience-vermiculite, cement-grit- granulated slag, porous concrete-slag wool, gritstone-glassine, limestone-thermoiz. concrete, asbestos cement-expanded clay-concrete, cement slabs-bakelite, quartz glass-teflon), as well as in the range of diameters of the inner and outer layers respectively (inner diameter of chamotte varied from 0.02 to 0.045 m, outer diameter of chamotte – from 0.05 to 0.07 m and outer diameter of asbestos – from 0.074 up to 0.15 m) was calculated;

4) graphs of dependences of inwall temperature on type of heat-insulating material, and also on thicknesses of external and internal layers inwall for pair "chamotte-asbestos" of the electric inductor were constructed.

As a result of the performed investigations the influence of external and internal layers thickness of a two-layer inwall, and also heat-insulating materials on the inwall temperature of the cylindrical inductor for heating the metal workpiece was established.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Бабичев А.П. Физические величины. Справочник / А.П. Бабичев, Н.А. Бабушкина, А.М. Братковский. Под ред. И.С. Григорьева, Е.З. Мейлихова. – М.: Энергоатомиздат, 1991. – 1232 с.

2. Духневич К.Л. Тепловий розрахунок індукційного нагрівача / К.Л. Духневич, О.В.Кравець. – XXI Міжнародна наук.-практ. конф. „Людина і космос", 10-12 квітня 2019. – с. 31.

3. Исаченко В.П. Теплопередача / В.П. Исаченко, В.А. Осипова, А.С. Сукомел. – М.: Энергоиздат, 1981. – 416 с.

4. Кузнецов Г.Ф. Тепловая изоляция. Справочник строителя / Г.Ф. Кузнецов. – М.: Стройиздат, 1985. – 303 с.

5. Никитина Е.А. Исследование и разработка трехфазного индуктора для нагрева цилиндрических заготовок в поперечном магнитном поле / Е.А. Никитина. – Дисс. на соиск. уч. степ. канд. техн. наук. – Самара, 2011. – 143 с.

6. Павлов Н.А. Инженерные тепловые расчеты индукционных нагревателей /Н.А. Павлов. – М.: Энергия, 1978. – 119 с.

7. Bolyukh V.F. Influence Of Geometrical Parameters Of the Inductor and Armature on the Indicators of a Linear Pulse Electromechanical Converter of an Electrodynamic Type / V.F. Bolyukh, Y.V. Kashanskij, I.S. Schukin // Electrical Engineering & Electromechanics. – 2019. – N. 3. – P. 11-17.
8. Chang L. Effect of Plate Curvature on Heat Source Distribution in Induction Line Heating for Plate Forming / L. Chang, Y. Zhao, H. Yuan, X. Hu, Z. Yang, H. Zhang // Applied Sciences. – 2020. – V. 10 – N. 7. – P. 99-115.
9. Frajer G. Dimensioning and shaping of inductors for power converters / G. Frajer, G. Delette, C. Rado, H. Chazal, P. Perichon, O. Isnard, F. Servant // EPE Journal. – 2017. – V. 27 – N. 3. – P. 98-105.
10. Glebov A.O. Modeling the Induction Heating of Press Equipment in an Automatic-Temperature-Control Mode / A.O. Glebov, S.V. Karpov, S.V. Karpushkin, E.N. Malygin // Journal Of Engineering Physics And Thermophysics. – 2019. – V. 92 – N. 5. – P. 1130-1141.
11. Lekomtsev S.V. Evaluation of the Temperature Regime of the Rods of the Inductor of an MHD Stirrer for Possible Use in an Industrial Aluminum Furnace / S.V. Lekomtsev, S.Y. Khripchenko // Journal of Applied Mechanics and Technical Physics. – 2018. – V. 59 – N. 7. – P. 1189-1196.
12. Niu C. Numerical Analysis of Eddy Current Induced by z-Gradient Coil in a Superconducting MRI Magnet / C. Niu, L. Wang, Y. Wang, Y. Zhai, H. Qu, Y. Liu, Q. Wang // Ieee Transactions On Applied Superconductivity. – 2020. – V. 30 – N. 4. – P. 295-303.
13. Serrano J. Design and Optimization of Small Inductors on Extra-Thin PCB for Flexible Cooking Surfaces / J. Serrano, I. Lope, J. Acero, C. Carretero, J. Burdio, R. Alonso // IEEE Transactions On Industry Applications. – 2017. – V. 53 – N. 1. – P. 371-379.
14. Yang Z. An Improved Design Method for Gapped Inductors Considering Fringing Effect / Z. Yang, H. Suryanarayana, F. Wang // Thirty-Fourth Annual IEEE Applied Power Electronics Conference And Exposition. – Anaheim, CA, MAR 17-21, 2019. – P. 1250-1256.

REFERENCES

1. Babichev A.P. Phizicheskie velichiny. Spravochnik / A.P. Babichev, N.A. Babushkina, A.M. Bratkovskiy. Pod red. I.S. Grigor‘eva, E.Z. Meylikhova. – M.: Energoatomizdat, 1991. – 1232 p.

ISSN 1562-9945 (Print)
ISSN 2707-7977 (Online)

2. Дukhnevich K.L. Teploviy rozrakhunok induktsiynogo nagrivacha / K.L. Dukhnevich, O.V. Kravets. – XXI Mizhnarodna nauk.-prakt. konph. „Ludina i kosmos", 2019, 10-12 April. – P. 31.
3. Isachenko V.P. Teploperedacha / V.P. Isachenko, V.A. Osipova, A.S. Sukomel. – M.: Energoatomizdat, 1981. – 416 p.
4. Kuznetsov G.Ph. Teplovaya izolyatsya. Spravochnik stroitelya / G.Ph. Kuznetsov. – M.: Stroyizdat, 1985. – 303 p.
5. Nikitina E.A. Issledovanie i razrabotka trekhphaznogo induktora dlya nagreva tsilindricheskykh zagotovok v poperchnom magnitnom pole / E.A. Nikitina. – Diss. na soisk. uch. step. cand. techn. nauk. – Samara, 2011. – 143 p.
6. Pavlov N.A. Inzhenernye teplovye raschety induktsionnykh nagrevateley /N.A. Pavlov. – M.: Energiya, 1978. – 119 p.
7. Bolyukh V.F. Influence Of Geometrical Parameters Of the Inductor and Armature on the Indicators of a Linear Pulse Electromechanical Converter of an Electrodynamic Type / V.F. Bolyukh, Y.V. Kashanskij, I.S. Schukin // Electrical Engineering & Electromechanics. – 2019. – N. 3. – P. 11-17.
8. Chang L. Effect of Plate Curvature on Heat Source Distribution in Induction Line Heating for Plate Forming / L. Chang, Y. Zhao, H. Yuan, X. Hu, Z. Yang, H. Zhang // Applied Sciences. – 2020. – V. 10 – N. 7. – P. 99-115.
9. Frajer G. Dimensioning and shaping of inductors for power converters / G. Frajer, G. Delette, C. Rado, H. Chazal, P. Perichon, O. Isnard, F. Servant // EPE Journal. – 2017. – V. 27 – N. 3. – P. 98-105.
10. Glebov A.O. Modeling the Induction Heating of Press Equipment in an Automatic-Temperature-Control Mode / A.O. Glebov, S.V. Karpov, S.V. Karpushkin, E.N. Malygin // Journal Of Engineering Physics And Thermophysics. – 2019. – V. 92 – N. 5. – P. 1130-1141.
11. Lekomtsev S.V. Evaluation of the Temperature Regime of the Rods of the Inductor of an MHD Stirrer for Possible Use in an Industrial Aluminum Furnace / S.V. Lekomtsev, S.Y. Khripchenko // Journal of Applied Mechanics and Technical Physics. – 2018. – V. 59 – N. 7. – P. 1189-1196.
12. Niu C. Numerical Analysis of Eddy Current Induced by z-Gradient Coil in a Superconducting MRI Magnet / C. Niu, L. Wang, Y. Wang, Y. Zhai, H. Qu, Y. Liu, Q. Wang // Ieee Transactions On Applied Superconductivity. – 2020. – V. 30 – N. 4. – P. 295-303.
13. Serrano J. Design and Optimization of Small Inductors on Extra-Thin PCB for Flexible Cooking Surfaces / J. Serrano, I. Lope, J. Acero, C. Carretero, J. Burdio,

R. Alonso // IEEE Transactions On Industry Applications. – 2017. – V. 53 – N. 1. – P. 371-379.
14. Yang Z. An Improved Design Method for Gapped Inductors Considering Fringing Effect / Z. Yang, H. Suryanarayana, F. Wang // Thirty-Fourth Annual IEEE Applied Power Electronics Conference And Exposition. – Anaheim, CA, MAR 17-21, 2019. – P. 1250-1256.

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Дослідження впливу параметрів двошарової футерівки циліндричного індуктора на її температуру

Розглядається дослідження теплового стану двошарової футерівки циліндричного індуктора для дванадцяти пар теплоізоляційних матеріалів. Наведено математичну модель процесу, схему циліндричного індуктора, таблицю пар досліджуваних теплоізоляційних матеріалів шарів футерівки. Розраховано та побудовано діаграму температури внутрішньої поверхні футерівки в залежності від пари матеріалів її шарів та графік зміни температури футерівки в залежності від товщин її шарів для пари „шамот-азбест”.

Исследование влияния параметров двухслойной футеровки цилиндрического индуктора на ее температуру

Рассмотрено исследование теплового состояния двухслойной футеровки цилиндрического индуктора для двенадцати пар теплоизоляционных материалов. Приведена математическая модель процесса, схема цилиндрического индуктора, таблица пар исследуемых теплоизоляционных материалов слоев футеровки. Рассчитана и построена диаграмма температуры внутренней поверхности футеровки в зависимости от пары материалов ее слоев, а также график изменения температуры футеровки в зависимости от толщин ее слоев для пары „шамот-асбест”.

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