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NUMERICAL SIMULATION OF ELECTROMAGNETIC AND THERMAL FIELDS IN INDUCTION CHANNEL FURNACES WITH DEFECTS OF LINING

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The numerical experiments and analysis of inhomogeneous distribution of electromagnetic and thermal fields in induction channel furnaces with various defects of their thermal insulation (lining) are carried out using finite element method and multi-physical modeling approaches. The problem is formulated in a nonlinear definition with strong mutual relations of subproblems for complex three-dimensional geometry. By the example of a furnace for melting of oxygen-free copper in the presence of leakage of the metal melt into furnace lining, the dependence of the temperature changes over the surface of the furnace body on the depth of penetration of the melt and its volume is determined. It is studied the changes in the temperature distribution inside of thermal insulation as it degrades, i.e. when each of the four layers of material is reached by melt. The emergency configurations of the melt leakage, which require the furnace to be shut down and replaced are determined, and the analysis of the existing situations observed on the casting lines at industrial plants is carried out. The application of the proposed calculation technique allows to control the state of induction channel furnaces and develop the recommendations for increasing their resource. References 12, figures 3.

Keywords: electromagnetic field, induction heating, numerical simulation, interrelated processes, copper melting, thermal insulation defects.

Introduction. At present, a special attention is paid to interdisciplinary (multi-physical) research, in which the processes described by laws from different fields of physics are investigated simultaneously [1]. And the progress in the development of numerical methods allows to solve the problems with larger data sets than previously [2]. This allows us to identify finer mechanisms of physical effects and take into account the nonlinear properties of materials [3] as well as the complexity of the three-dimensional geometry of the objects under study [4]. This paper is devoted to solving the problem that includes all these three aspects simultaneously – the calculation of the interrelated electromagnetic and thermal processes during induction heating of copper in the induction channel furnaces. Though there are many studies devoted to induction heating, for example [5–7], at the present time there is insufficient information about the regularities of the inhomogeneous distribution of electromagnetic and thermal fields in heterogeneous media with defects of various configurations. In practice the detection of furnace lining defects is carried out now indirectly [8] and there is no method or software product that allows to determine the specific dimensions or location of internal melt leakage. Therefore, these studies are relevant both from the point of view of development of the theory, and for the elaboration of new industrial equipment and improvement of existing one.

The aim of the work is calculation of the inhomogeneous distribution of electromagnetic and thermal fields in the induction channel furnaces and determination of the regularity of changes these fields depending on the defects configuration in the thermal insulation of furnaces.

Physical-mathematical problem definition. The problem was formulated as one consisting of an electromagnetic and a thermal subproblem with strong mutual relations [1, 9]. As an example, the induction channel furnace of the UPCAST US20X-10 (Fig. 1) for melting oxygen-free copper was considered. The furnace was supplied from 50 Hz sinusoidal voltage transformer, with an operating power range of 80–400 kW. Since the time constants of the considered processes differ by 5–6 orders (the period of electromagnetic oscillations is $2\cdot10^{-2}$ s, and the duration of heating is 10^3–10^4 s), then the electromagnetic subproblem was solved in the frequency domain, and the thermal subproblem – in the time domain, as in [6, 10]. The electromagnetic field was calculated in the linear approximation using the effective value of the relative magnetic permeability μ_{eff} of the inductor magnetic circuit calculated according to magnetization curve.

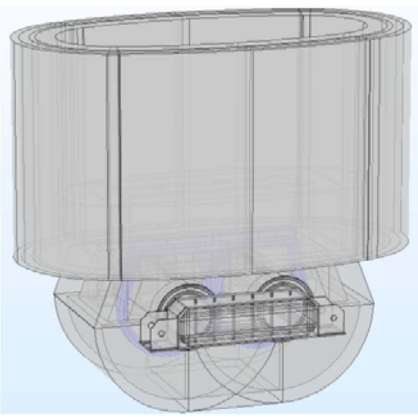

Fig. 1

Electromagnetic subproblem. To calculate the distribution of the magnetic field and the current density, the system of Maxwell equations with respect to the vector potential $\vec{A}$ was solved [11]. The calculated equations for various elements of the inductor and furnace were derived in the same way as in [10] and have the form:

a) for the copper melt in the inductor channel and in the furnace:

$$\mathrm{rot}\,[\mu_0^{-1}\mathrm{rot}\,\dot{\vec{A}}] + j\omega\sigma(T)\dot{\vec{A}} = 0\,; \qquad (1)$$

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b) for copper inductor bus wire: $\mathrm{rot}\,[\mu_0^{-1} \mathrm{rot}\, \dot{\vec{A}}] - \dot{\vec{J}}_{ext} = 0$; (2)

c) for the steel core of the inductor: $\mathrm{rot}\,[(\mu_0 \mu_{eff})^{-1} \mathrm{rot}\, \dot{\vec{A}}] = 0$; (3)

d) for the lining mixture of the inductor, the four-layer brickwork of the furnace, the water in the tubes of the cooling system of inductor and furnace: $\mathrm{rot}\,[\mu_0^{-1} \mathrm{rot}\, \dot{\vec{A}}] = 0$. (4)

Here $\vec{J}_{ext}$ is the current density vector in the inductor buses, $\sigma(T)$ is the conductivity of copper, which is a function of temperature T and is described by the following equation:

$$\sigma(T) = 1/[\rho_0 (1 + \alpha(T - T_{ref}))], \quad (5)$$

where ρ_0 = 1.72·10^{-8} Ω·m is the specific electric resistance of copper, α = 3.9·10^{-8} K^{-1} is a temperature coefficient of resistance of copper, T_{ref}= 273.15ºK is the reference temperature.

The computational domain was three-dimensional one and it consisted of volume of the inductor and the furnace with a copper melt, the contact of which with the ambient air was described by the boundary conditions on their bodies. Equations (1)–(4) were joined by boundary conditions at the interfaces of the elements and supplemented by the Dirichlet conditions $\vec{n} \cdot \vec{A} = 0$ on the boundaries of the computational domain.

Thermal subproblem. To calculate the distribution of the thermal field in the furnace lining and inductor, the heat balance equation was solved as in [10]:

$$\rho C_p \, \partial T / \partial t - \nabla \cdot (k \nabla T) = Q_{eddy} + Q_{water}, \quad (6)$$

Here ρ, C_p and k are the density, heat capacity and thermal conductivity of the materials, Q_{eddy}, Q_{water} are the heat sources including metal heating by eddy current Q_{eddy} and cooling of the busses and lining when water flows through the pipes of the cooling system Q_{water}.

The heat rejection by the water was calculated according to the equation:

$$Q_{water} = M_t \cdot C_p \, (T_{in} - T)/V. \quad (7)$$

Here M_t – water flow (in kilograms) passing through the cross section of the tubes per unit time, T_{in} – incoming water temperature, V – internal volume of the system pipes.

Copper heating by eddy currents realizes a multi-physical connection between the electromagnetic and thermal subproblems and it is specified in the form:

$$Q_{eddy} = \dot{\vec{E}} \cdot \vec{J}^* = \omega^2 \sigma(T) \dot{\vec{A}} \cdot \vec{A}^* . \quad (8)$$

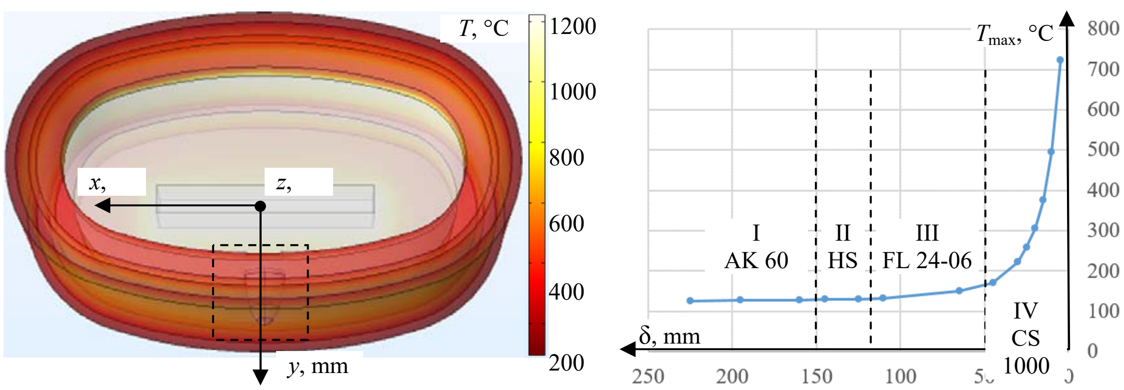
The system of equations (6)–(8) was supplemented by the boundary conditions of heat transfer by means of thermal conductivity at the interfaces of the elements and by the conditions of convective heat rejection from the inductor body and furnace with the help of a given heat transfer coefficient h according to the equation:

$$-k \, \partial T / \partial n = h(T - T_{ext}) . \quad (9)$$

Here T_{ext} is the ambient air temperature, $\boldsymbol{n}$ is the normal vector to the outer boundary.

The systems of differential equations (1)−(4) and (6)−(8) were solved by the finite element method in the program package Comsol Multiphysics [12].

Discussion of the numerical experiment results. The leakage of the copper melt into the furnace lining was modeled by a half ellipsoid of rotation with semiaxis a, b and c, which are parallel to orts in Cartesian coordinates x, y, z (xy is the bottom plane of the furnace, and z is the normal to this plane). The center of the ellipsoid was located on the boundary of the melt and lining of the furnace wall in the symmetry center of the cross-section xz (x = 1350 mm, y = 470 mm), as shown in Fig. 2, a. The value of z = 475 mm with a melt height of 950 mm. The semiaxis of the ellipsoid $a = b$ = 100 mm, which is an example of the specific size of the metal leakage [4], and the semiaxis c varies with intervals of 5 mm from 50 mm to d = 275 mm – the total thickness of all four layers of the furnace lining.



a **Fig. 2** *b*

For each configuration of the ellipsoid, the temperature distribution along the surface of the furnace body and its maximum value T_{max} at the hottest point were determined. The characteristic of the depth of penetration of the metal into the lining was the value $\delta = d - c$, i.e. $\delta = 0$ in the absence of leakages and $\delta = 275$ mm when the melt reaches the furnace body. An example of the temperature distribution T over the furnace body for a value $\delta = 270$ mm is shown in Fig. 2, *a*, and the dependence of the value of T_{max} on δ for the investigated range of configurations of internal lining defects is shown in Fig. 2, *b*.

As shown in Fig. 2, *a*, the lining of the furnace is 4 layers of thermo-insulating material: 1^{st}, 2^{nd} and 3^{rd} layers are Silrath AK 60, Durrath HS and Porrath FL 24-06 bricks respectively, and 4^{th} layer is calcium silicate plate CS 1000. The graph in Fig. 2, *b* is divided into 4 zones depending on the depth of penetration of the melt according to number insulation layers, which metal has overpass. When the melt penetrates into the first layer of bricks (275 mm > δ > 150 mm), the temperature on the furnace body increases in no more than 5° C compared to its normal value of T_{norm} = 125° C. When the melt penetrates into the second layer (150 mm > δ> 115 mm), the temperature increases in no more than 10° C. When the melt passes the third layer (115 mm > δ> 50 mm), the temperature can rise in 26° C. The main temperature differences occur when the melt reaches the last fourth layer of lining (50 mm > δ> 0 mm) and directs to the metal furnace body. This case is characterized by an increase in temperature on the body from 45° C to hundreds of degrees theoretically.

So UPCAST as one of the largest manufacturers of induction furnaces for melting copper recommends that its operation is stopped and lining of the furnace is changed when the temperature on furnace body reaches 250–300° C. In particular, at the PJSC Yuzhcable Works, where the UPCAST US20X-10 casting line operates currently, the maximum temperature on the furnace body is T_{max} = 254° C [4]. According to the results of a numerical experiment, if such temperature is observed on the body, the penetration depth of the melt into the lining is 250 mm. This case is extremely dangerous, since the distance to the furnace body is only 25 mm.

Fig. 3 shows the change in temperature T in the volume of the lining without defects along the *y*-axis shown in Fig. 2, *a*, (dashed curve 1) and in the presence of a melt leakage into the lining to a depth of 250 mm (solid curve 2). In the absence of melt leakage, the main temperature drop in 900° C occurs in the III and IV layers of the brick with a total thickness of 115 mm (Fig. 2, *a*), while the temperature on the body is equal to 125° C, which corresponds to the normal operation of the furnace. When a melt leakage occurs, such temperature drop happens only in a part of the IV layer of a brick with 25 mm thick, which results in the temperature increase to 254° C. In addition, the temperature gradient G_T increases in the remaining part of the IV layer. This fact has a negative effect on the lining material and reduces its working life.

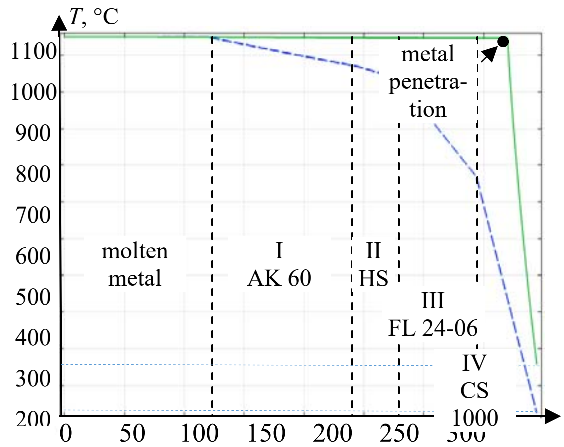


Fig. 3

The use of the proposed technique allows to perform more accurate control and diagnostics of the lining state of the induction channel furnaces, creating the basis for forecasting and recommendations for increasing furnace working life. Analyzing the rate of metal melt leakage into the lining, it is possible to correct the furnace technological modes aimed at optimizing the production capacity and slowing the degradation processes in thermal insulation.

Also, the information obtained is useful for more accurate prediction of the remaining time prior to the occurrence of an emergency situation and makes it possible to prepare equipment and materials for a planned replacement of the furnace.

Conclusion. 1. Using finite element method and multiphysical modeling approaches, the numerical experiments and analysis of inhomogeneous distribution of electromagnetic and thermal fields in induction channel furnaces are carried out when various defects of their thermal insulation appear. The problem is formulated in a nonlinear definition with strong mutual relations of subproblems for complex three-dimensional geometry.

2. The dependence of the change in a temperature over the furnace body surface on the depth of penetration of the melt and its volume (during melt reaches each of the four layers of material) is determined. After penetration of the melt into the first layer of insulation, the temperature on the furnace body increases in no more than 5° C compared to its normal value T_{norm} = 125° C. When the melt penetrates into the second layer, the temperature increases in no more than 10° C, and when the melt passes the third layer the temperature can rise in 26° C. The main increase in the temperature occurs when the melt reaches the last fourth layer of the lining. Such case is characterized by an increase in temperature on the body from 45° C to hundreds of degrees.

3. Emergency configurations of the melt leakage, which require the furnace to be shut down and replaced are determined, as well as an analysis of existing situations observed on casting lines at industrial plants is carried out. The use of the proposed technique allows to perform more accurate diagnostics of the lining state of induction channel furnaces, creating the basis for forecasting and recommendations for increasing their working life.

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ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ ЕЛЕКТРОМАГНІТНОГО І ТЕПЛОВОГО ПОЛІВ В ІНДУКЦІЙНИХ КАНАЛЬНИХ ПЕЧАХ З ДЕФЕКТАМИ ФУТЕРОВКИ

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Використовуючи метод кінцевих елементів і підходи мультифізичного моделювання проведені чисельні експерименти і аналіз неоднорідного розподілу електромагнітного і теплового полів в індукційних канальних печах при виникненні різних дефектів їх термоізоляції (футеровка). Задача формулюється в нелінійній постановці з сильними взаємними зв'язками підзадач для складної тривимірної геометрії. На прикладі печі для плавки безкисневої міді при протіканні розплаву металу в її футеровку визначена залежність зміни температури на поверхні корпусу печі від глибини проникнення і об'єму розплаву. Досліджено зміни в розподілі температури всередині термоізоляції по мірі її деградації, тобто по мірі досягнення розплаву кожного з чотирьох шарів матеріалу. Визначено аварійні конфігурації протікань розплаву, які вимагають зупинки печі і її заміни, а також проведено аналіз існуючих ситуацій, що спостерігаються на лініях лиття на промислових підприємствах. Застосування запропонованої методики розрахунку дозволяє контролювати стан індукційних канальних печей і розробляти рекомендації зі збільшення їхнього ресурсу. Бібл. 12, рис. 3.

Ключові слова: електромагнітне поле, індукційний нагрів, чисельне моделювання, взаємопов'язані процеси, плавка міді, дефекти теплоізоляції.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ЭЛЕКТРОМАГНИТНОГО И ТЕПЛОВОГО ПОЛЕЙ В ИНДУКЦИОННЫХ КАНАЛЬНЫХ ПЕЧАХ С ДЕФЕКТАМИ ФУТЕРОВКИ

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Используя метод конечных элементов и подходы мультифизического моделирования, проведены численные эксперименты и анализ неоднородного распределения электромагнитного и теплового полей в индукционных канальных печах при возникновении различных дефектов их термоизоляции (футеровки). Задача формулируется в нелинейной постановке с сильными взаимными связями подзадач для сложной трехмерной геометрии. На примере печи для плавки бескислородной меди при протекании расплава металла в ее футеровку определена зависимость изменения температуры на поверхности корпуса печи от глубины проникновения и объема расплава. Исследованы изменения в распределении температуры внутри термоизоляции по мере ее деградации, т.е. по мере достижения расплавом каждого из четырех слоев материала. Определены аварийные конфигурации протеканий расплава, требующее остановки печи и ее замены, а также проведен анализ существующих ситуаций, наблюдаемых на линиях литья на промышленных предприятиях. Применение предложенной методики расчета позволяет контролировать состояние индукционных канальных печей и разрабатывать рекомендации по увеличению их ресурса. Библ. 12, рис. 3.

Ключевые слова: электромагнитное поле, индукционный нагрев, численное моделирование, взаимосвязанные процессы, плавка меди, дефекты термоизоляции.

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