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HYDRODYNAMIC CALCULATION OF THE POWER CIRCUIT OF THE COMPLEX FOR ELECTROCHEMICAL PROCESSING

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ГИДРОДИНАМИЧЕСКИЙ РАСЧЕТ СИЛОВОЙ ЦЕПИ КОМПЛЕКСА ДЛЯ ЭЛЕКТРОХИМИЧЕСКОЙ ОБРАБОТКИ

Purpose. Hydrodynamic calculation of flow of the electrolyte in the interelectrode gap of electro-technical complex for the dimensional electrochemical machining
Design/methodology/approach. The most significant scientific and applied results, conclusions and recommendations are as follows: for the first time invited to the dependence of the total resistance of the interelectrode gap from electrical, hydraulic and geometric parameters. Set the U-shaped dependence of the resistance of the working current, which leads to its instability, that is, for the first time theoretically explained by the frequent appearance of the regime of a short circuit when electrochemical processing; for the first time considered the inductance of the interelectrode gap, which helped to create a more accurate mathematical model of the complex.
Proposed the mathematical model of the power circuit of electro-technical complex for electrochemical treatment of metals and alloys, which allows you to: correct in theory to calculate the values of the operating current; theoretically explain the property of self-regulation interelectrode gap (the presence of the derivative in the law regulation).
Findings. The essence of the carried out researches is in the theoretical explanation of the properties of self-regulation interelectrode gap and the possibility of a regime of a short circuit, as well as in the theoretical calculation of the operating current of the complex depending on its electrical, geometric and hydraulic parameters.
Originality/value. Proposed the mathematical model of the power circuit of electro-technical complex for electrochemical treatment of metals and alloys, which allows you to: correct in theory to calculate the values of the operating current; theoretically explain the property of self-regulation interelectrode gap (the presence of the derivative in the law regulation).
Keywords: hydrodynamic calculation, electrochemical machining, spark plug gap, nonlinear resistance, acid.

Introduction

At present, the industry and household appliances widespread got asynchronous motor with short-closed rotor. This is explained, first of all, with their low cost (compared to other motors and simplicity. However, now the prices for aluminum in Ukraine is set at the level of the world, which leads to a rise in the cost of electric motors.

In these circumstances it becomes an urgent task repair of asynchronous engines. If before, in the times of the USSR, often engine repair cost more than his workmanship, now more profitable to restore the rotors. Since practically all the enterprises for the production of electrical machines were founded in 1991, they lack workshop for the restoration of the rotors, which now results in a loss, because the defective engines have to be thrown away.

Broken bars in the rotor - a defect that occurs very often. Operation of the engine even at one-two shabby either side leads to the subsequent failure of the other rods and motor failure in the work.

Short-closed the rotor winding is a flooded into the grooves of electrical steel (covered with a special film) aluminium rods of complex configuration (fig. 1). These rods are interconnected rings from the same aluminum, which are cast together with them for one casting cycle.

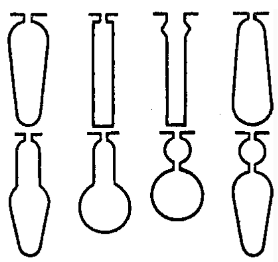

Fig. 1. The form of slots in the rotor of induction motors

Once you have determined the precipice of a particular rod in the rotor, the problem of the removal. Theoretically destruction of rods it is possible in several ways: aluminium smelting of slots when heated to a temperature of 700 OS; chemical alkaline solution, drilling and milling slot.

Unfortunately, it turned out that all of these methods cannot be applied in practice. Therefore, in our University has been proposed for solution of this task, use the dimensional electrochemical machining of 11. The essence of the method consists in reception of on-site rod holes who repeats the shape and size of himself slot.

Dimensional electrochemical machining is used for the electrically conductive materials. To its advantages include the possibility of obtaining long and narrow hole of the complicated configuration, high class of accuracy, absence of residual stresses, etc.

But with all the advantages of electrochemical processing has some disadvantages, and high power consumption - the most significant of them. Therefore, the task of optimization of control systems includes not only the increase of accuracy of processing, but also the reduction of energy. For this it is necessary to develop adequate model of the power circuit of the electrical complex [2].

For the synthesis of energy-efficient system of management of the process of electrochemical treatment need to get the mathematical description of the control object which acts as a spark gap.

The existing mathematical models of the interelectrode gap received provided of sufficiently strong assumptions and do not take into account the impact of certain significant factors.

A very important process parameter is the current density. It is clear, that for increase of productivity of process of electrochemical process it is desirable to maintain the density of the operating current at the level of the maximum level. It is intuitively clear that the limit value of current density should depend on electrical parameters (electric field strength), parameters of the electrolyte (its viscosity and flow, as well as the initial concentration of electrolyte and geometric parameters of size cathode-tool and interelectrode gap. And unfortunately, in the literature there are no quantitative relationships between these variables.

In addition to the existing models of the power circuit, in our view, is a very strong assumption of the constancy of the electrical conductivity of electrolyte and its resistance regardless of the speed of the electrolyte and the operating current; is not taken into account the regime of flow of the electrolyte, etc. [3].

Research objective

For the design of control system for complex for electrochemical treatment of metals that will provide high performance, precision and low power consumption, necessary to have a mathematical model of the control object i.e. the power circuit of the complex.

Basic maintenance and results of research

To the power circuit of electro-technical complex for electrochemical treatment includes power supply, connecting cables and transformer, column of the electrolyte to the cathode-tool spark plug gap and the anode.

While the structural scheme of the transformer and power sources are known, the equivalent circuit of interelectrode gap requires scrutiny and improvement. In the existing literature provides simplified schemes, which do not take into account a number of very important factors, one of the main is the current electrolyte in the interelectrode gap [4].

The most significant drawback of all known mathematical models, is, in our opinion, a very strong assumption that the electrical conductivity of the electrolyte and the current limit consider constant regardless of the speed of the electrolyte and the operating current.

For a more precise definition of dependence of the current limit of hydraulic, geometrical and electrical parameters in [2] proposed the following approach: first you need to find the velocity field of the electrolyte in the interelectrode gap with the decision of the equations Navier-Stokes then using the found velocity distribution solve the equation of diffusion to obtain field electrolyte concentration according to the

$$\frac{\partial C}{\partial t} + \vec{v}\, grad\, C = D\nabla^2 C \tag{1}$$

where C is the concentration of the electrolyte, $\vec{v}$ is the speed of the electrolyte, D is the diffusion coefficient, t - time.

Then determined by the maximum density of the current, which flows in the interelectrode gap, according to the expression

$$j_{пред} = D\, grad\, C + \frac{DmF\vec{E}}{RT} C\,, \tag{2}$$

where m - is valence ions of electrolyte, R is the gas constant, T is the temperature of the electrolyte Kelvin, F is Faraday constant, $\vec{E}$ is the electric field intensity in the interelectrode gap.

The found values of current density at a given concentration of the electrolyte and the electric field strength are determined by the components of the full effective resistance of interelectrode gap:

$$Z_0 = \frac{RT}{F^2 D_1 D_2 m_1 m_2}\,, \tag{3}$$

$$Z_1 = \frac{RT(m_1 + m_2)}{F m_1 m_2 (i_{пред} - i)}\,, \tag{4}$$

$$Z_2 = \frac{2RT}{Fi}\,. \tag{5}$$

where $i_{пред}$ is the current limit, i is the operating current.

At the decision of this problem we made the following assumptions: electrode was round, and electrolyte and incompressible Newtonian liquid.

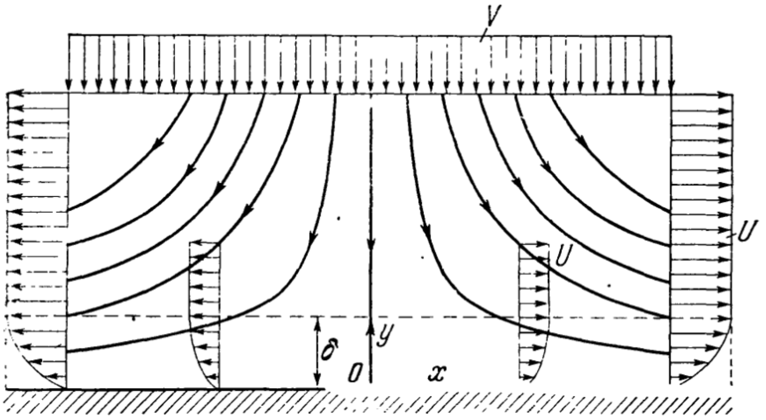

Fig. 2. The fluid near the critical point

To determine the velocity field of the electrolyte between the electrode gap consider the spatial axisymmetric flow of a viscous fluid near the critical point. Liquid flowing on the wall, that perpendicular to the direction of motion, and flows from the critical point along the wall (fig.2). For this case there is the exact solution of the equation Navier-Stokes [5]. The taskis solved in cylindrical coordinate system r, φ, z. The plane $z = 0$ aligned with the wall, and and the axis of the is directed oppositely stream.

Let U and V is the radial and axial velocity of the flow of an ideal fluid, and $u(r, z)$ and $v(r, z)$ the corresponding rate for viscous currents. As a result of axial symmetry $v_\varphi = 0$ and $\partial/\partial\varphi = 0$. Therefore, equation Navier-Stokes equation and the continuity equation is of such seeing:

$$v\frac{\partial v}{\partial r} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \gamma\left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r}\frac{\partial v}{\partial r} - \frac{v}{r^2} + \frac{\partial^2 v}{\partial z^2}\right),$$

$$v\frac{\partial w}{\partial r} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \gamma\left(\frac{\partial^2 w}{\partial r^2} + \frac{1}{r}\frac{\partial w}{\partial r} + \frac{\partial^2 w}{\partial z^2}\right),$$

$$\frac{\partial v}{\partial r} + \frac{v}{r} + \frac{\partial w}{\partial z} = 0$$

where p is the pressure of the electrolyte, ρ is the density, γ is the kinematic viscosity.

The boundary conditions:

$$v = 0, \quad w = 0 \quad при \quad z = 0,$$
$$v = V \quad при \quad z = \infty.$$

To solve the equation Navier -Stokes equations is used affine conversion. Ultimately obtained an expression for the electrolyte velocity:

$$w = 2\left(\frac{Q}{2\pi r_k^2 d}\right)^{\frac{b+1}{2}} \gamma^{\frac{b-1}{2}} g z^b e^{G\sqrt{\frac{Q}{2\pi r_k^2 d\gamma}}z}. \tag{6}$$

Radial electrolyte velocity is

$$v = \frac{Q}{2\pi r_k^2 d} r \left(1 - e^{-\sqrt{\frac{Q}{\pi r_k dT}}z}\right),$$

where $T = 0.7$, Q - is electrolyte flow, r_k is the radius of the cathode-tool, d is spark gap, $a = \frac{Q}{2\pi r_k d}$, $g = 0.2358, b = 1.807, G = 0.0466$.

The expression for the velocity of the electrolyte is used for determining the allocation of its concentration, and the largest radial velocity is checked, the assumption that the diffusion boundary layer is relatively small in comparison with the surface of the anode.

Distribution of the concentration of the electrolyte is determined by the decision of the diffusion equation (5).

We write the expression for the maximum current density, considering the distribution of the concentration of the electrolyte, according to (2):

$$j_{пред} = Da_1 e^{\frac{1}{D}\int_0^\infty w(z)dz} + \frac{DmF\vec{E}}{RT} a_1 e^{\frac{1}{D}\int_0^\infty w(z)dz},$$

in this expression $w(z)$ is defined by the expression (6).

In our case, the current limit in the still electrolyte is equal to 0.44 A, while for mobile electrolyte current limit is equal to 10.58 A (in practice, the current is 9-10 A).

The found values of current limit will find a complete effective resistance interelectrode gap, consisting of the ohmic resistance (3), diffusion (4) and migration (5) resistance.

Here the dependence of the total resistance of the interelectrode gap of the operating current (fig.3) (description of the calculated in relative units). As you can see the characteristic impedance has a U-shaped form, which is explained by the predominance of the different stages of electrochemical reaction diffusion whether migration voltage and resistance respectively. The presence of the incident site on the characteristic may cause the instability of the process, that is, to the fluctuations of the current. This explains the frequent occurrence mode short circuit in practice.

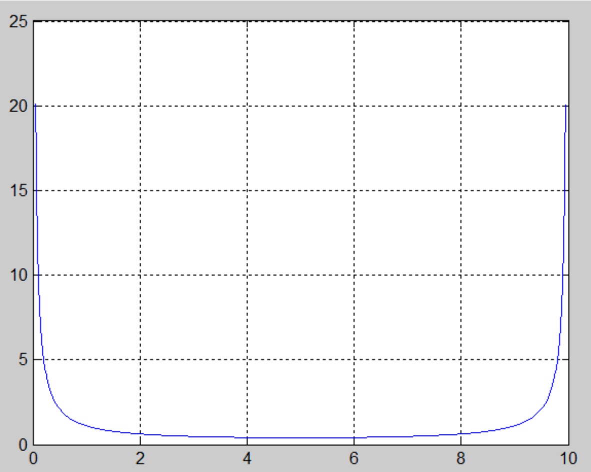

Fig. 3. Dependence of the total resistance of the interelectrode gap of the operating current in relative units

Specific capacity interelectrode gap is equal to 16-20 μF/cm^2.

Its equivalent inductance is determined depending on the type of power source for the time of the payment of non-stationary electrochemical process. For the first time the question of non-stationary phenomena in heterogeneous process of the details were studied by A.N. Sokolov, then V.G. Levich [4]. When this is the assumption of the constancy of the time rate of flow of the electrolyte. We assume that the process of transition is over 3 time constants, then when supplied with power from a voltage source

$$T_u = \frac{1}{3}\sqrt[3]{\frac{\gamma}{\pi D v^3}} ,$$

and when supplied with power from the current source

$$T_u = \left(\frac{nF}{2j}\right)^2 \pi D C_0 .$$

Inductance $L_{зaз}$ is defined as the time constant, is divided into $R_{зaз}$. You have to understand, that the active resistance of the interelectrode gap $R_{зaз}$ is the sum of the ohmic, diffusion and migration of resistance (7-9).

Thus, the spark plug gap is precipitate-oscillating link with the transfer function

$$W_{зaз} = \frac{R_{зaз}\left(\frac{L_{зaз}}{R_{зaз}} p + 1\right)}{p^2 C_{зaз} L_{зaз} + p C_{зaз} R_{зaз} + 1} . \qquad (7)$$

The presence in the transfer function of the interelectrode gap precipitate link gives him a certain preventive properties, because the system is introduced in addition to the variable and its derivative, that is the tendency to change. This confirms the adequacy of the mathematical model of the interelectrode gap, which, as is known from the practice of [3], has the property of self-regulation.

According to the above relationships, you can calculate the parameters of the structural scheme of the power circuit of electro-technical complex for electrochemical treatment. According to the results of counting, as expected, it turned out that the inductance and capacitance of connecting wires can be neglect other same size must be taken into account.

Then, after some transformations one can obtain the transfer function of the power circuit of electro-technical complex in the following form:

$$W = \frac{1}{R_E + R_{зaз}} \frac{T_{зaз} p + 1}{\frac{T_{зaз} L_E}{R_E + R_{зaз}} p^2 + Tp + 1} , \qquad (8)$$

where $R_E = R_{un} + R_{mp} + R_{aн} + R_{np} + R_{cm}$, $L_E = L_{mp} + L_{aн}$, $T = \frac{T_{зaз} R_E + L_E + L_{зaз}}{R_E + R_{зaз}}$, $T_{зaз} = C_{зaз} R_{зaз}$.

Thus the power circuit is described by the serial connection of nonlinear and the two inertial links because damping factor is more 1 always.

Be aware that permanent can be considered only in the active resistance of the power supply, cables and transformer (as well as its inductance). Resistance same electrolyte, the capacity of the column electrolyte and inductance of the interelectrode gap and anode depend on the value of operating current and are non-linear. The resistance of the anode is changed when it is dissolved.

Thus, for the first time we received a structural scheme of the power circuit of the electrical engineering complex for electrochemical treatment, which takes into account the inductance and capacitance of the interelectrode gap, the parameters of the column the electrolyte to the cathode instrument and their dependence on the operating current, non-linear nature which, as is not difficult to show, may result if the supply of the complex from the source of EMF before the fluctuations of the current and the termination of the process (which is quite often happens in practice). A mathematical model is proposed to explain this phenomenon.

With the transfer function of the power circuit (8) one can obtain the expression for the operating current (numerical coefficients obtained with the constant values)

$$pI = \frac{0.87I^2 + \left(3.59 - 0.87I_{пред} - U\right)I + \left(U - 7.17\right)I_{пред}}{L\left(I_{пред} - I\right)} . \qquad (9)$$

Differential equation (9) fails to submit in the form of the Cauchy problem. However, it has a solution in implicit form

$$\frac{\left(I^2 - 28.89I + 146.93\right)^{0.127}\left(2I - 44.59\right)^{0.072}}{\left(2I - 13.18\right)^{0.072}} = e^{-t} - 0.72 .$$

This permissions are represented graphically in fig. 4.

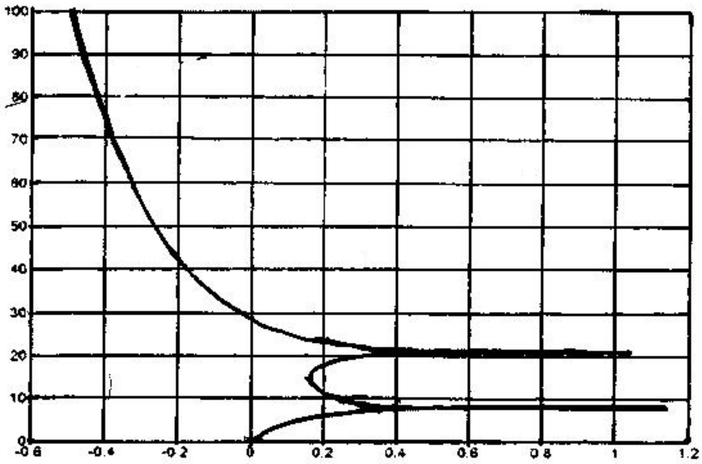

Fig. 4. The dependence of the operating current of time

As can be seen in figure 4 for some values of the time there are two, three or four different current values. In our opinion, the existence of two points of bifurcation and ambiguity of the current values may lead to his hesitation, what if the current is стремится to large values of the maximum permissible (in our case, 10 (A), there will be a short circuit. As is known, this phenomenon has repeatedly arises in practice.

This ambiguity arises through a non-linear dependence of the resistance of the interelectrode gap of the AC. Neglect of the previous research of this dependence and ambiguity (in our well-known literature resistance of electrolyte in the interelectrode gap is generally considered to be constant and independent of the current strength) are not allowed to explain the frequent occurrence mode short circuit and, therefore, to take measures to prevent it.

Figure 5 shows the dependence of a current from time to time, obtained under the assumption of the constancy of the resistance. As you can see, it is completely repeats the lower branch of the characteristics in figure 5, but does not allow to get two more of its branches and to provide for the possibility of instability of the operating current.

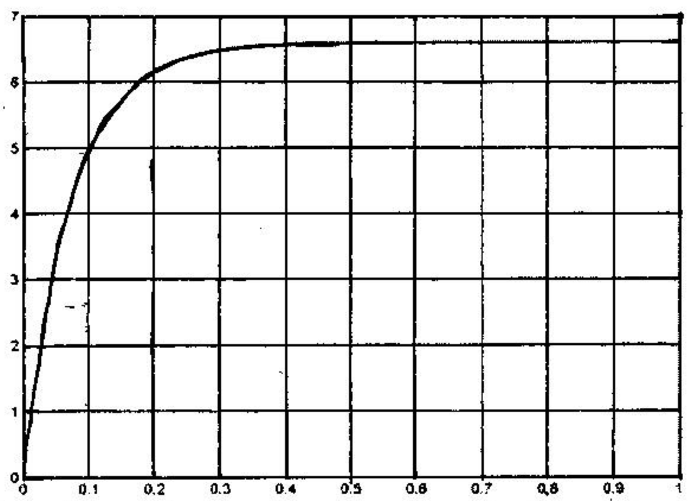

Fig. 5. The dependence of the operating current from time to time under the assumption of constant resistance

Thus, the obtained mathematical model of the power circuit of electro-technical complex for the dimensional electrochemical machining can be considered adequate, because it allows you to use the correct theoretically calculate the values of the operating current; theoretically explain the property of self-regulation interelectrode gap (the presence of the derivative in the law regulation); theoretically substantiate the possibility of regime (short-circuit protection at the expense of a nonlinear U-shaped dependence of the total resistance of the interelectrode gap of the operating current, a branch is may lead to instability of the process).

Summary

The paper provides theoretical generalization and solving actual scientific-technical tasks of the mathematical model of the power circuit of electro-technical complex for the dimensional electrochemical machining

The essence of the carried out researches is in the theoretical explanation of the properties of self-regulation interelectrode gap and the possibility of a regime of a short circuit, as well as in the theoretical calculation of the operating current of the complex depending on its electrical, geometric and hydraulic parameters.

The most significant scientific and applied results, conclusions and recommendations are as follows:

1. For the first time invited to the dependence of the total resistance of the interelectrode gap of hydraulic, power and geometric parameters. Set the U-shaped dependence of the resistance of the working current, which leads to its instability, that is, for the first time theoretically explained by the frequent appearance of the regime of a short circuit when electrochemical processing.

2. For the first time presents the dependence of accounting for non-linear resistance of a column of the electrolyte to the cathode instrument.

3. For the first time considered the inductance of the interelectrode gap and the anode, which helped to create a more accurate mathematical model of the complex.

4. For the first time proposed the mathematical model of the power circuit of electro-technical complex for electrochemical treatment of metals and alloys, which allows you to:

- correct in theory to calculate the values of the operating current;
- theoretically explain the property of self-regulation interelectrode gap (the presence of the derivative in the law regulation).

Анотація. *Теоретично визначені поля швидкостей і концентрацій електроліту у міжелектродному проміжку комплексу для електрохімічної обробки, що дозволило знайти значення граничної щільності струму в електроліті і робочий струм у ньому і пояснити саморегульованість міжелектродного проміжку і виникнення режиму короткого замкнення. Поле швидкостей знайдено як точне розв΄язання рівняння Нав΄є-Стокса для течії біля критичної точки. Поле концентрації визначено як розв΄язок рівняння дифузії з урахуванням розподілу швидкостей електроліту.*

Ключові слова: гідродинамічний розрахунок, електрохімічна обробка, міжелектродний проміжок, нелінійний опір, електроліт.

Аннотация. *Теоретически определены поля скоростей и концентрации электролита в межэлектродном зазоре комплекса для электрохимической обработки, что позволило найти значение граничной плотности тока в электролите и рабочий ток в нем и объяснить саморегулируемость межэлектродного зазора и возникновение режима короткого замыкания. Поле скоростей найдено как точное решение уравнения Навье-Стокса для течения в окрестности критической точки. Поле концентрации определено решением уравнения диффузии с учетом распределения скоростей электролита.*

Ключевые слова: гидродинамический расчет, электрохимическая обработка, межэлектродный зазор, нелинейное сопротивление, электролит.

1. *Спосіб* відновлення литих короткозамкнених обмоток роторів: Пат. України № 77041: МПК H02K 15/00, H02K 15/08 - Опубл. 16.10.2006, Бюл. № 10.
2. *Заблодский Н.Н.* Обоснование и выбор источника питания для комплекса электрохимической обработки металлов // Технічна електродинаміка. – 2004. - № 5. – С. 68-74.
3. *Орлов В.Ф.* Электрохимическое формообразование – М.: Машиностроение, 1990.
4. *Левич В.Г.* Физико-химическая гидродинамика – М.: Изд-во Академии наук СССР, 1952.
5. *Шлихтинг Г.* Теория пограничного слоя – М.: Наука, 1974.

REFERENCES

1. *Method* of restoration of the cast squirrel cage rotor windings: Patent Ukraine No. 77041: Int.Cl. N02K 15/00, N02K 15/08., Pub. 16.10.2006, Bulletin no. 10.
2. *Zablodskij N.N.* Substantiation and choice of power source for the complex of electrochemical machining of metals. Tehnichna elektrodinamika, 2004, no 5, pp. 68-74.
3. *Orlov V.F.* Electrochemical shaping. Moscow: Mashinostroenie, 1990.
4. *Levich V.G.* Physico-chemical hydrodynamics. Moscow: Izd-vo Akademii nauk SSSR, 1952.
5. *Shlihting G.* Theory of boundary layer. Moscow: Nauka, 1974.