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Substantiation of the temperature regime of the differential pump of electromagnetic action

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The article discusses the temperature of the working body caused by Foucault currents circulating inside of the working body of a differential pump of electromagnetic action. The article begins with a theory describing the nature of the Foucault current and the causes of the plunger heating. Then there is a characteristic of the differential pump of electromagnetic action. The following is a description of the structures of the working bodies of the differential pump of electromagnetic action. The estimated data of the working body are entered in the table. These tables are taken into account when plotting. The theory substantiates the conditions of heating of the working body, the existence of eddy currents, and also the influence of the temperature of the actuator on the operation of the differential pump. The description shows what role the plunger plays in the operation of the differential pump. The article described in detail the interaction of the working body and the solenoid of the differential pump.

Keywords: differential pump, finishing mixture, plunger, Foucault current

Обґрунтування температурного режиму роботи диференціального насоса електромагнітної дії

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У статті досліджується зміна температури робочого органа диференційного насоса електромагнітної дії, що спричинюється струмами Фуко в середині цього робочого органа. Розглянуто теоретичні основи виникнення вихрового струму та причини нагріву плунжера. Наведено опис конструктивних особливостей та розрахункові хараетристики різних типів робочих органів диференційного насоса електромагнітної дії. Теоретично обґрунтовано умови нагріву робочого органа диференційного насоса та існування шкідливих струмів, а також вплив температури плунжера на роботу диференційного насоса. Досліджено вплив плунжера на технічні характеристики диференційного насоса. Описано взаємодію робочого органу та котушки диференційного насоса електромагнітної дії, а також вплив геометричних особливостей на величину температури нагріву плунжера та пагубних струмів. Від вибору матеріалу з якого можна виготовить робочий орган залежить температури нагріву плунжера і величина несприятливого струму. Проведено детальний опис всіх процесів котрі відбуваються в робочому органі. Представлені та детально описані характеристики робочих органів які виготовлені з різного матеріалу та методом порошкової металургії. Це загалом дає можливість аналізувати конструкцію плунжера диференційного насоса електромагнітної дії. За рахунок ретельного вибору матеріалу а також конструкційної особливості робочого органа диференційного насоса вдалося отримати суттєву економію електроенергії, що було детально розкрито в таблиці та показано на графіках температурно опірної характеристики (ТОХ).

Ключові слова: диференціальний насос, оздоблювальна суміш, плунжер, струм Фуко.

Introduction

Today in Ukraine there are about 800 models of pumps, which differ in their principle of operation, performance, power, discharge pressure, and the structure of the working bodies. However, the problem of increasing their economic efficiency while ensuring high reliability remains particularly acute. One of the ways to solve this problem is to reduce the material consumption of the product and reduce electricity consumption during operation [1, 7]. In turn, this requires the introduction of new science-based pump designs or design changes to existing models.

Review of the research sources and publications

Initial data on the differential pump are obtained as a result of standard acceptance tests of the design in the laboratory. The main purpose of this data is to improve the performance of the differential pump. In addition, the results of statistical tests of the pump affect the design standards. This process was especially intensified with the invention of other pump designs [7]. Numerous publications since the 1950s [1 – 12] are devoted to the statistical description of the mechanical characteristics of the design of a differential pump, in particular its performance. This is especially true of the reliable statistical parameters of the pump performance required to increase the transport of the finishing material. This is emphasised, in particular, in the publications prepared by the scientific school "Creation of theoretical foundations for calculation, design, and implementation of effective means of complex mechanisation of finishing works in construction" of the National University “Yuri Kondratyuk Poltava Polytechnic” [1].

Definition of unsolved aspects of the problem

Currently, the problem of creating pumps for which a minimum amount of construction materials are used is quite acute. Manufactured pumps consume a minimum amount of electricity while having maximum performance. The operation of such pumps is short. Now the urgent task is to create a differential pump of electromagnetic action, which is able to work rationally. The differential pump of electromagnetic action is able to provide an increased level of efficiency during operation to 52% with long service life.

With a large number of differential pumps of electromagnetic action, their design diversity is very large. The manufacture of a differential pump of electromagnetic action, which consumes a small amount of electricity, is an urgent problem for the development of the pumping industry.

Problem statement

The aim of the article is to highlight the results of research of the plunger differential pump of electromagnetic action intended for pumping construction finishing mixtures. Analysis of literature sources on this topic and experimental studies show that in the working body of such a pump there is a loss of energy to heat the plunger and solenoid winding, which leads to reduced efficiency. The cause of heating is the Foucault current, which begins to circulate in the working body when moving the plunger. It is proposed to minimize the negative impact of Foucault current by breaking the closed-loop of the magnetic circuit, namely by using a separate plunger or a plunger made by powder metallurgy.

In order to create a cost-effective model of the differential pump of electromagnetic action and its further implementation in production, the following tasks are solved:

- the factors leading to energy losses in the working body of the differential pump of electromagnetic action are revealed;
- by selecting the material of the plunger and due to its separate structure, the formation of Foucault currents in the working body is minimised and, accordingly, energy losses for heating are reduced, which increases the efficiency of the pump;
- in order to reduce the heating temperature of the plunger, a large working body was created to reduce the temperature caused by Foucault currents;
- in order to determine the mode of operation of the differential pump at which the pump will consume a minimum of electricity at maximum capacity, a graph of the temperature-resistance characteristic is created.

Basic material and results

The research is carried out on a plunger differential pump of electromagnetic action, the structure of which is shown in Figure 1.

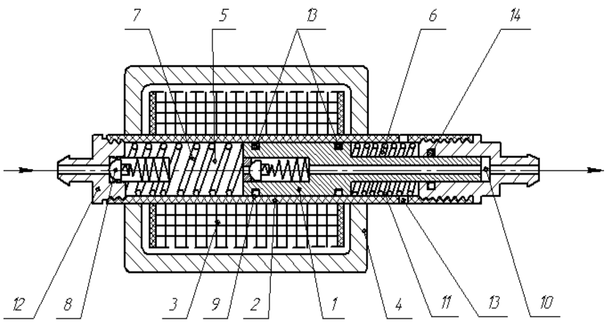

Figure 1 – Differential pump of electromagnetic action:
1 – plunger; 2 – housing; 3 – electromagnet winding; 4 – a magnetic circuit of the winding; 5 – suction cavity; 6 – compensating spring; 7 – working spring; 8 – suction valve; 9 – discharge valve; 10 – compensation chamber; 11,12 – injection and suction fittings; 13, 14 – cuff seals

The pump of the proposed structure works as follows. When a current is applied to the solenoid winding 3, an electromagnetic field is generated, which causes the plunger 1 to move towards the suction valve 8 by compressing the working spring 7. The finishing mixture, which is present in the suction cavity 5, is also compressed. It causes the discharge valve 9 to open and is fed through the hole in the plunger to the discharge fitting 12. After stopping the supply of current under the action of the working spring 7, the plunger 1 returns to the opposite position creating a vacuum in the suction cavity 5. Under the influence of the vacuum suction valve 8 opens and the finishing mixture fills the cavity 5. Next, the winding 3 is again supplied with current and the cycle is repeated.

The electromagnetic differential pump has no auxiliary mechanical gears, so its efficiency is higher than other pump models. However, there is a disadvantage associated with the loss of energy in the drive.

The operating cycle of the pump consists of two stages, each of which is accompanied by the movement of the plunger. Because the plunger has a certain resistance, when it moves in a magnetic field there are Foucault currents, which are harmful because they lead to loss of energy to heat the plunger. In this case, the operation of the pump becomes economically unprofitable.

Given that the maximum value of Foucault current reaches in a closed circuit, it is advisable to use a separate plunger or plunger made by powder metallurgy, which allows breaking the circuit and reducing the negative impact of Foucault currents [1, 8].

Thus, the process of pumping the mixture by the pump consists of two cycles; each cycle depends on the process of Foucault's current initiation in the plunger and is associated with the magnetic flux flowing in the magnetic circuit.

Under the action of alternating current in the coil, there is the generation of magnetic flux in the magnetic circuit. The magnetic field density is 57.4 T. The density of the magnetic field generates voltage. As the magnetic flux density increases, the voltage increases. Foucault's current is formed as a result of the interaction of voltage and resistance. Increasing the frequency of the network produces an increase in Foucault's current. The plunger is heated as follows. The magnetic flux interacts with the plunger to form an EMF. EMF and resistivity create Foucault's current. The plunger heats up.

The differential pump [1, 8] has a coil that passes current and a working body that pumps the finishing mixture. The plunger and the coil are connected by a metal magnetic core. When current is applied through the magnetic circuit, the magnetic flux in the plunger will be voltage. The maximum Foucault current is generated in the working bodies of the closed circuit. The coil heats up. The eddy current will reduce the magnetic flux density. The decrease in magnetic field density is directly proportional to the electromotive force. This disturbs the balance between the voltage of the coil supplied from the socket and the EMF of the self-induction of the coil. The coil current will increase. As the current in the coil increases, the magnetic field density increases when the plungers of the open circuit equilibrium are restored. Heating the plunger reduces the coil current. Therefore, the occurrence of Foucault current in closed-loop plungers causes an increase in current in the working coil of the pump, heating the plunger. This makes the use of a differential pump economically impractical.

Thus, the process of Foucault currents in the plunger is associated with the magnetic flux flowing in the magnetic circuit and depends on the heating temperature of the plunger.

A voltage is applied to the coil of a differential pump from the mains, which together with the coil resistance depends on the following parameters: resistivity of the wire from which the coil is wound, length of the coil wire, and cross-sectional area of the wire. The electric current generates a magnetic inductance that depends on the dielectric constant of the vacuum, the current circulating in the coil, the number of turns of the coil, and the length of the solenoid core. Magnetic inductance produces a magnetic flux in the magnetic circuit that depends on the magnetic induction, the cross-sectional area of the coil, and the angle between the magnetic induction vector and the perpendicular to the cross-sectional area of the coil core. The magnetic flux produces an electromotive force in the working body of the differential pump, which in turn depends on the speed of the plunger, the magnetic induction of the coil, the circular length of the working body, and the position of the differential pump. The electromotive force together with the resistance of the working body consisting of the resistivity of the material, the circular length of the working body, the area of the longitudinal section of the plunger forms a Foucault current.

The Foucault current depends on the frequency (control value) and the frequency is inversely proportional to the length of the plunger, its mass, and the resistance of the working body. Due to the Foucault current, the working body is heated and the magnetic inductance is formed in the direction opposite to the magnetic inductance of the coil, which depends on the magnetic permeability of the material, Foucault current circulating in the working body, and radius of the working body. The temperature of the plunger is related to the Foucault current and the reactance of the differential pump coil. The reactance of the coil depends on the frequency of the current and magnetic induction. Magnetic induction depends on the following parameters: the number of turns of the coil, the cross-sectional area of the coil core, the length of the wire from which the coil is wound, the magnetic permeability of the vacuum, the magnetic permeability of the plunger, and the time required for maximum plunger heating. The magnetic inductance of the working body creates a magnetic flux also inversely proportional to the magnetic flux generated by the solenoid. Therefore, the coil of the differential pump takes more electricity than working with a cut plunger. The retraction force of the plunger depends on the number of turns of the coil, the length of the wire from which the coil is wound, and the Foucault current circulating in the plunger of the differential pump. The performance of the differential pump is the product of the suction force on the cross-sectional area of the plunger.

The differential pump has an air gap between the working body and the coil and does not have various auxiliary mechanical parts and therefore the efficiency of the differential pump of electromagnetic action is higher than in other models of pumps.

Since the translational movement of the plunger of the differential pump does not depend on the direction of the current transmitted to it, each differential pump can be driven by alternating current. However, in this case, its power is significantly reduced. The reason for this is that alternating current, passing through the coil, creates in the magnetic circuit so-called Foucault currents, the formation of which is a significant part of the electrical energy transmitted to the pump. In addition, in DC pumps, the excitation energy of the coil is consumed only once at the beginning of the action, after which the magnetization of the magnetic conductors remains unchanged. In a differential AC pump, the magnetic conductors are re-magnetized with each change in the direction of the current, which consumes some energy.

Heating of the working body causes power losses during operation. These include losses due to current heating of the coil of the differential pump, heating of the magnetic circuit from hysteresis and eddy currents, and to some extent due to heating from friction with air.

Seven working bodies of the differential pump are considered in the work. Each plunger, depending on the magnitude of the Foucault currents, has its own heating temperature. Each plunger was made of different materials or has a different structure (Figs. 2 – 15).

In Fig. 16 is shown a working body with dimensions. For further calculations, the plunger is imaginarily divided into two cylinders. The volumes and areas of the longitudinal sections are added.

Figure 2 – Plunger with a diameter of 23 mm

Figure 3 – Working body with a diameter of 30 mm

Figure 4 – Working body with a diameter of 23 mm

Figure 5 – Plunger with an important diameter of 30 mm

Figure 6 – Plunger with a diameter of 30 mm

Figure 7 – Plunger with a thickness of 23 mm

Figure 8 – Plunger with a thickness of 30 mm

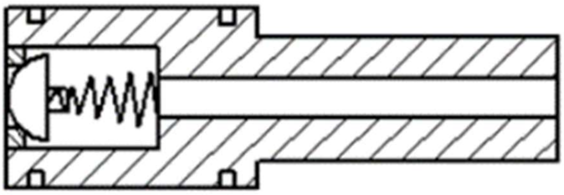

Figure 9 – Working body made of steel

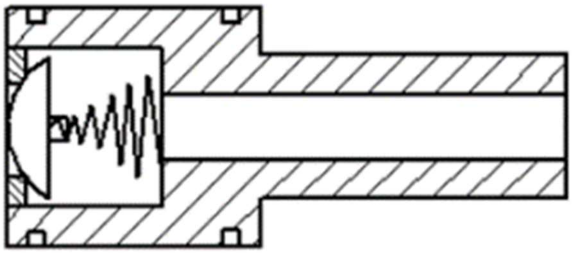

Figure 12 – Plunger made of steel

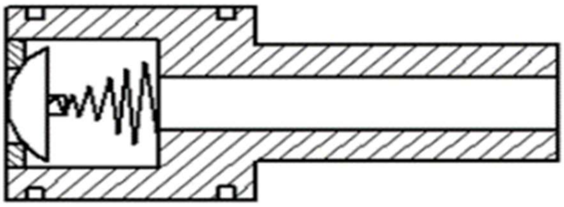

Figure 10 – Working body made of cast iron

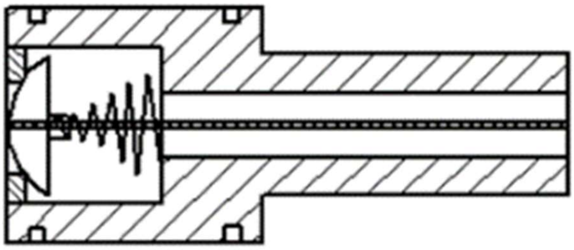

Figure 13 – Plunger made of steel (split)

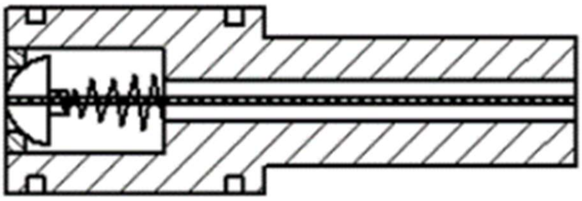

Figure 11 – Working body made of steel (separate)

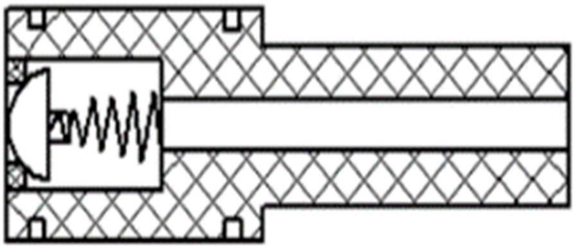

Figure 14 – Plunger made of ground iron

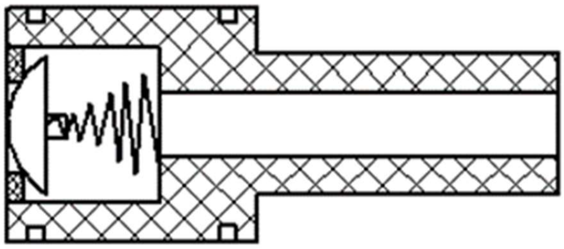

Figure 15 – Plunger made by powder metallurgy method

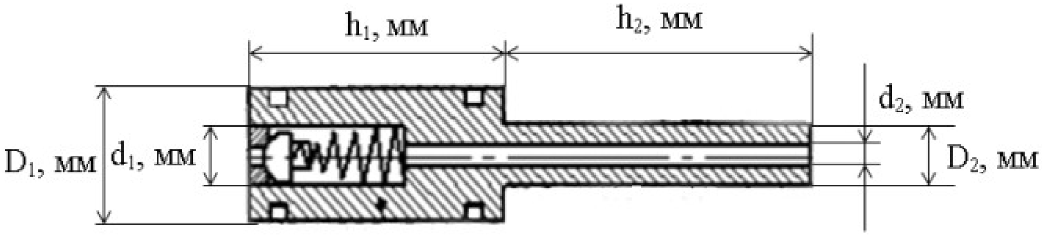

Figure 16 – Sketch of the working body of the differential pump

In the mathematical description of the process of heating the plunger, it is considered as two hollow cylinders with a resistivity of a certain value. Consider the case where the plunger is in a uniform magnetic field. The resistance of the plunger at known dimensions of the working body is determined [6] as

$$R_{work} = \rho \cdot \frac{l}{S_1} \ , \qquad (1)$$

where ρ is the resistivity;
l is the length of the solenoid, m;
S_1 is the area of the longitudinal section of the plunger, mm^2.

Since the frequency of the alternating current in the network from which the pump is fed has known (50 Hz), the amount of current circulating in the working body has found [9] by Foucault's law

$$I = \frac{W}{R} \ , \qquad (2)$$

where W is a current frequency, Hz;
R is the resistance of the working body, Ohm.

If the plunger has a solid structure, then Foucault's currents circulate in it. The heating temperature of the plunger is found [6] according to the Joule-Lenz law using the reactance of the solenoid winding

$$T = I^2 \cdot X_L \cdot t \ , \qquad (3)$$

where I is Foucault current, A;
X_L is the reactance of the winding, Ohm;
t is the time required for maximum heating of the plunger, s.

Taking into account that part of the thermal energy is transferred from the working body to the pumped medium, according to the Joule-Thompson formula [4] the degree of cooling of the plunger is determined

$$t = m \cdot c\ (t_i - t_f)\ , \qquad (4)$$

where m is the weight of the plunger, kg;
c is the specific heat of the working body, kJ/(kg·K);
t_i is an initial temperature of the working body, ^{0}C;
t_f is the final temperature of the working body, ^{0}C.

Thus, the values of voltage U, current I, and operating time t form the work of the electric current, and Q_0, Q_m form the efficiency of mechanical action which on the basis of experimental studies forms the efficiency of the differential pump of electromagnetic action [5]

$$\eta = \frac{A_u}{A_i} + \frac{N_T}{N} \cdot 100\% \ , \qquad (5)$$

where: A_u – useful work, J;
A_t – total work, J.

The electromotive force that moves the plunger may be determined from experimental data on the heating temperature of the working body, the time of its operation, and the reactance of the solenoid winding

$$u = \sqrt{\frac{T \cdot X_L}{t}} \ , \qquad (6)$$

where T – heating temperature of the working body, ^{0}C;
X_L – reactance of the winding, Ohm;
t is the operating time of the pumps.

The value of the Foucault current is obtained on the basis of data on the heating temperature of the working body, the operating time of the pump, and the reactance of the winding

$$I = \sqrt{\frac{T}{X_L \cdot t}} \ , \qquad (7)$$

The research is conducted for plungers of solid and separate structures made of different materials. Steel, cast iron, and iron powder are chosen as the plunger material (Figs. 2 – 8).

The conducted calculations and studies show the following. Foucault currents are present in solid steel with a diameter of 23 mm (Fig. 2), cast iron, and steel with a diameter of 30 mm (Fig. 3, 4) plungers. The resistance of the plungers, determined by dependence (1) is minimal. In this case, according to Ohm's law, Foucault's currents reach maximum values.

Separate steel plungers with a diameter of 23 mm (Fig. 5) and a diameter of 30 mm (Fig. 6), as well as made by powder metallurgy with diameters of 23 mm (Fig. 7) and a diameter of 30 mm (Fig. 8) have maximum resistance and therefore, they have infinitesimal Foucault currents.

Studies of Foucault currents values depending on the geometric dimensions (diameter) of the plunger show the following: eddy current value in a steel plunger with a diameter of 23 mm is less than a steel plunger with a diameter of 30 mm, and it is more than in a plunger made of cast iron with a diameter of 30 mm.

The plunger is made of steel with a diameter of 30 mm due to the minimum frequency and has lower Foucault current values. The steel plunger with a diameter of 23 mm has the maximum frequency and therefore has the highest value of Foucault current. The plunger made of cast iron has a medium frequency and therefore the value of the Foucault current is intermediate.

Depending on the material and geometric dimensions, the heating temperature in steel plunger with a diameter of 23 mm is 374 ^{0}C, in cast iron plunger with a diameter of 30 mm is 264 ^{0}C, in steel plunger with a diameter of 30 mm is 286 ^{0}C. As can be seen, the steel plunger with a diameter of 23 mm has a higher heating temperature than the plunger with a diameter of 30 mm. This is due to the more intense heat dissipation from the plunger of larger diameter.

The 30 mm steel plunger has a higher heating temperature than the 30 mm cast iron working body due to the different electromotive forces given in the working body.

Although separate plungers have no energy loss due to heating, their use is not advisable, as they cannot withstand high pumping pressures. Thus, for a working body with a diameter of 23 mm, the maximum pressure is 0.8 MPa, for a working body with a diameter of 30 mm it is 0.5 MPa.

It should also be noted that the plunger made by powder metallurgy might contain different amounts of the metal component due to which you can adjust the magnetic susceptibility of the plungers.

Tables 1 – 2 show the main physical quantities that were obtained as a result of the study. Some of the results, such as Foucault's current values, plunger heating temperature, and pumping heating temperature, were obtained by calculation, and the other part was obtained as a result of the experiment. The operating time of the solenoid winding is taken in random order. The initial temperature of the plunger and its heating temperature, the resistance of the solenoid winding were determined experimentally.

Table 1 – Physical effect of the plunger temperature on the pumping of the finishing material

No	Plunger type	Magnetic flux *Ф*, Wb	The maximum heating temperature of the plunger *t*, ^{0}C	Retraction force $\vec{F}$ *F*, N	Pumping pressure *P*, MPa
1	Steel with diameter 23 mm	310	374	39,2	0,18
2	Cast iron with diameter 30 mm	190	264	54	0,15
3	Steel with diameter 30 mm	149	286	49	0,1

Table 2 – Physical parameters of the differential pump of electromagnetic action

No	Plunger type	Theoretical data					Practical data						
		Reactive winding resistance X_L, Ohm	EMF plunger *U*, V	Foucault current *I*, A	Plunger heating temperature	Plunger temperature during pumping *t*, °C	Winding time *t*, min	Reactive winding resistance X_L, Ohm	EMF plunger *U*, V	Foucault current *I*, A	Initial temperature of the plunger *t*, °C	Plunger heating temperature	Plunger temperature during pumping *t*, °C
1	Steel *d* = 23 mm	27130	32	2,4	60	– 19,4	5	13502	51,4	23,3	18	70	– 5,4
2	Steel *d* = 30 mm		65,1	2	304	– 29			50,2	15		75	– 7
3	Cast iron *d* = 30 mm		58	2,1	46	– 3			31	3		35	– 3

Note: The sign "–" means endothermic process.

The graph presented in Figure 17 shows the dependence of the heating temperature of the plunger on the winding resistance. Lines 1, 2, 3 are obtained by calculation and show the change in the physical parameters of steel plungers with diameters of 23 and 30 mm, and cast iron plunger with a diameter of 30 mm. Analysing the graphical dependencies, it can be seen a rapid increase in the heating temperature of the steel plunger at a constant resistance. Maximum temperatures of plungers have the following values: 320 ^{0}C, 46 ^{0}C, 304 ^{0}C. Lines 4, 5, 6 show the dependence of the temperature of the plungers at constant resistance, which is obtained experimentally. The temperatures of the plungers have the following values 70 ^{0}C, 35 ^{0}C, 75 ^{0}C.

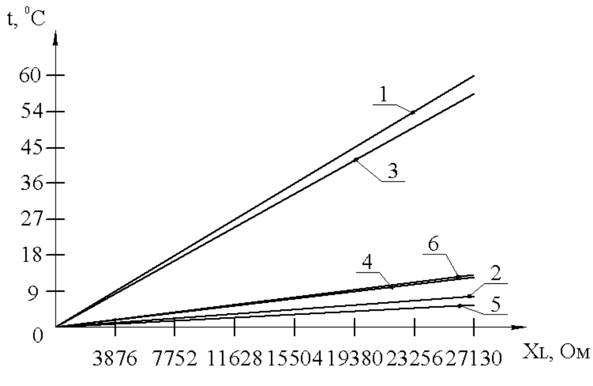

Figure 17 – Graph of the dependence of the heating temperature of the plunger on the winding resistance:
1, 2, 3 – respectively, a steel plunger with a diameter of 23 mm and a diameter of 30 mm, a cast iron plunger with a diameter of 30 mm (theoretical values); 4, 5, 6 – respectively steel plunger with a diameter of 23 mm and a diameter of 30 mm, a cast iron plunger with a diameter of 30 mm (experimental values)

Figure 18 illustrates a three-dimensional graph of the dependence of the heating temperature of the plunger on independent factors, built in the Excel software environment. The reactive resistance of the differential pump winding with a step of 714 Ohms is plotted on the abscissa axis. The heating temperature of the plunger with a step of 17.5 ^{0}C is plotted on the ordinate axis. The operating frequency with a step of 13 Hz is plotted on the axis of the application. The operating frequency of the plunger was found experimentally. Their analysis allows concluding that most of the heating temperature of the pump plunger is influenced by the frequency of translational movements. To ensure proper performance at balanced energy costs, it can be recommended the following ranges of parameters: density of finishing mixture ρ = 1045 kg / m^3; the frequency of translational movements of the plunger of the differential pump n = 50 Hz

If the frequency of translational movements of the working body of the differential pump will be increased, on the one hand, it will lead to a sharp increase in the heating temperature of the plunger, and on the other hand, in the general case, to increase the pumping intensity of the finishing material. But, given the peculiarities of the studied differential pump, in which the working body is inextricably linked with the mortar, the increase in the frequency of its translational motion is limited. Therefore, based on the previous considerations, taking into account the graphical dependencies (Figs. 17 – 18) and analytical expression (2), we can recommend the operating value of the translational frequency of the plunger of the differential pump equal to 50 Hz.

Comparing the experimental data (Fig. 17, lines 4, 5, 6) with the values of the heating temperature of the plunger of the differential pump calculated by the theoretical dependence (4), it can be concluded that the discrepancy in the results does not exceed 10%. Moreover, within the basic operating frequencies of translational motion (about 50 Hz) the coincidence is quite accurate, which confirms the necessary accuracy of the proposed theoretical method.

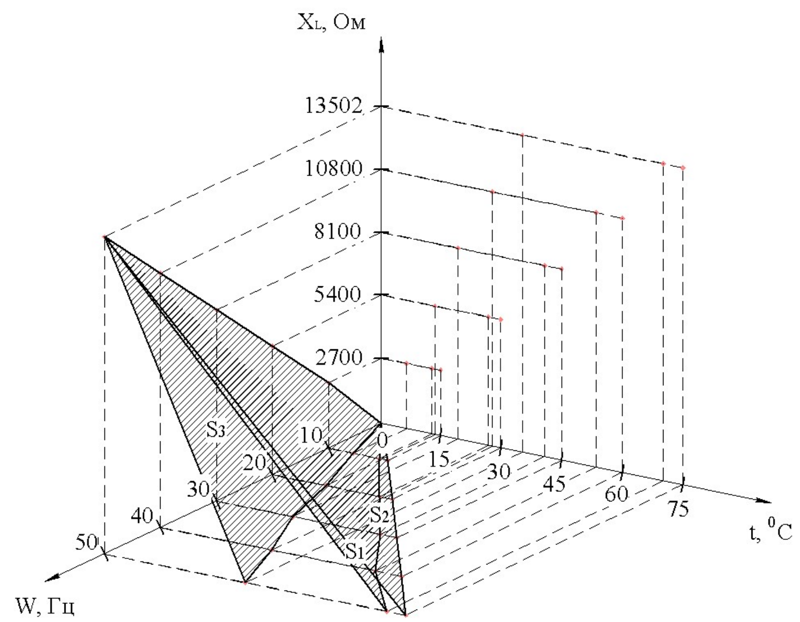

Figure 18 – Three-dimensional graph of temperature-resistance characteristics

S_1 t, ^{0}C = 2, 4617E-11+1.4*X+3,0717E-11*Y

S_2 t, ^{0}C = 6,1456E-11+1,5*X+7,6764E-11*Y

S_3 t, ^{0}C = 1,2308E-11+0,7*X+1,5359E-11*Y

Conclusions

In the examination of the working bodies of the differential pump, it should be noted that each plunger is made of different material and therefore has a different resistivity. A three-dimensional graph has three different planes intersecting at a common point. Therefore, the differential pump works productively under the following conditions, frequency 50 Hz, reactance 13502 Ohm, and temperature 35^{0}C.

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