METHOD OF POWER OPTIMIZATION IN GEOTHERMAL HEATING SYSTEM BY SOLVING INTERRELATED PROBLEMS OF ACOUSTIC AND MAGNETIC DEVICE MODEL

Valery Korzhakov, Alexey Korzhakov, Svetlana Korzhakova
Adyghe State University, Russia
korve@yandex.ru, korhakov-av@yandex.ru

Abstract. The paper presents the research results of the mutual influence of pulse voltage, magnetic field strength gradient, and thermal regime for the energy consumption of an acoustic magnetic device. To carry out the research, a hypothesis has been put forward on the possibility of increasing the energy efficiency of the acoustic magnetic device due to the joint solution of three problems: electric, magnetic and thermal. For the experimental study of the hypothesis, a model of an acoustic-magnetic device was developed using the ELCUT 6.1 software. In the process of modelling a geometric model was created, the physical properties of the model blocks, electrical circuit were established. The laws for distribution of temperature both inside and on the surface of the device under long-term operating conditions, since incomplete use of heating possibilities leads to a low-power electromagnetic field and to deterioration of magnetic processing, and overheating leads to destruction of interlayer insulation and turn-to-turn short circuit. The value of the temperature inside the pipeline through which the processed substance passes, since in the acoustic magnetic treatment of certain substances the temperature limits are strictly set, non-observance of which leads to unsatisfactory results. The obtained results show the possibility of reducing the power consumption of the acoustic magnetic device due to the use of pulse voltage of the meander type, ferrite ring as a radiator and magnetic circuit, and also a special material of the acoustic magnetic device body.

Keywords: modelling, ELCUT, acoustic magnetic device, superheat temperature.

Introduction

There is a situation that industrial enterprises are forced to spend huge amounts of money to fight with hard deposits (scale) occurring in cooling systems and thermal-power devices on the surface of heating or cooling. The resulting scale reduces the heat transfer, reduction in the cross-section of the pipes, or decrease in the period of exploitation and productivity of the equipment used.

Reducing the pipe cross-section makes it necessary to increase the pressure in the system, which leads to additional power consumption by the electric pumps.

Cleaning of the equipment and pipes from scale is a time-consuming and expensive process, involving violation of the equipment operation, with the purchase and use of chemical reagents. Geothermal energy needs complete replacement of all pipes after each heating season.

Currently, for descaling in the production process devices of magnetic treatment are used. In fact, they are permanent magnets or electro-magnets.

They are relatively simple in design and inexpensive, but their main drawbacks include the significant consumption of electric power by machines with a relatively small effect of preventing from scale formation.

One way to solve the existing problem is to introduce non-reagent methods of cleaning various systems from scale [1].

A new method of non-reagent treatment, based on the combination of acoustic and rotating magnetic fields in the working zone, is proposed. The new method will be called acoustic magnetic [2]. By means of acoustic magnetic treatment it is possible to slow the formation of inorganic deposits significantly, to reduce the rate of internal corrosion, to remove the film of fungi and bacteria from the inner surface of pipelines, without interruptions in the system, without interference in the operation of the system, without reagents and harm to the environment. Devices of appropriate power are mounted over the pipeline.

The implementation of the method is based on an acoustic magnetic device, which has obtained several patents [3-6]. The acoustic magnetic device can be used in various industries, including heat power engineering. An important factor is the efficiency of liquid treatment.

One of the main factors influencing the operation of the system is considered to be the thermal regime of the acoustic and magnetic device. The design parameters of the device are established in the process of modelling in the ELCUT environment.

Materials and methods

To define the ways of increasing the power efficiency of the acoustic and magnetic device it is necessary to study its thermal regime, suggest a model allowing to jointly solve three interconnected tasks, which are electrical, magnetic, thermal, and analyze the dynamics of the device heating. Based on the theoretical surveys and modelling, to design a model of the device and test it. Alongside with solving the heat exchange problem, the issue should be solved with the device capacity optimization, which can be successfully done, if reducing substantially the power consumption.

The literature devoted to the calculation of the thermal regime of the electromagnetic devices operation proposes many approaches. The disadvantage of the above methods is the use of a large number of empirical values (for example, thermal resistances), which depend on dimensions and other parameters of electromagnetic devices. Therefore, it is practically impossible to construct a mathematical thermal model of electromagnetic devices, which could correspond to a wide range of nominal powers of electromagnetic devices. In addition, with these approaches, the design parameters are considered constant, independent of the temperature of the electromagnetic devices, which does not correspond to reality – in fact, the ohmic resistance of the winding wires depends on the temperature. For the same reason, it is impossible to study the law of change in the heating temperature of electromagnetic devices depending on time. The author proposes a model of the thermal regime of the acoustic magnetic device, which allows not only to calculate the steady-state thermal regime, but also to analyze the dynamics of heating. In this case, the model contains only one empirical coefficient, which is the heat transfer coefficient. When designing a model of an acoustic-magnetic device, the system is considered to be with distributed parameters. This approach is due to the fact that the sources of heating of the acoustic-magnetic device, windings and magnetic circuit can be considered isotropic sources of heat. This assumption was made for the following reasons: firstly, the windings are distributed evenly over the entire area of the magnetic circuit; secondly, due to the very high thermal conductivity of the materials of the windings and the magnetic core (copper and ferrite) the windings thermal flows "intermix" with the magnetic circuit so to say, and thirdly, the magnetic circuit is homogeneous for the heat flow in all directions. The heat coming from the windings of the acoustic magnetic device is dissipated through its outer surface into the environment. The heat flux from the magnetic circuit is diverted to the surrounding space, passing through the internal interface between the windings of the acoustic-magnetic device and the magnetic core. There is an insulating material inside, which disrupts the homogeneity of the heat flow. To simplify the mathematical model, it is possible to ignore the thermal processes occurring at the internal interface. The settled superheat temperature of the acoustic-magnetic device depends on the efficiency of heat removal from its surface. The efficiency of heat removal is determined by the heat transfer coefficient, which characterizes the power extracted from a surface unit with a temperature change by one degree. The value of the coefficient depends on the cooling conditions. Thus, for example, the released power by the acoustic-magnetic device placed on a pipeline of a geothermal source with the temperature of about 87 ºK affects critically the superheat temperature of the device. Solving the problem of heat exchange, we simultaneously solve the power issue – the problem of optimizing the power output of the device. To successfully solve this problem, it is necessary to reduce the power consumption substantially.

In accordance with the law of convective heat transfer (Newton's law) [7], we assume that the heat flux is proportional to the difference between the ambient temperature and the surface of the acoustic-magnetic device.

Calculation of the thermal regime of the acoustic magnetic device is connected with calculation of the temperature field, which always presents certain difficulties. On the other hand, there is no need to know the exact value of the superheat temperature at each point of the acoustic magnetic device. Therefore, the conclusion is as follows, i.e. to consider only the average overheating temperature, depending on the time. This approach allows us not only to determine the superheat temperature of the acoustic-magnetic device, but also to estimate the dynamics of the thermal process. The calculation of the thermal regime of the acoustic-magnetic device is based on the classical heat conductivity equation written in cylindrical coordinates:

$$\frac{\partial T}{\partial t}-\frac{\lambda}{c\rho}\left(\frac{\partial^2 T}{\partial r^2}+\frac{1}{r}\frac{\partial T}{\partial r}+\frac{1}{r^2}\frac{\partial^2 T}{\partial \varphi^2}+\frac{\partial^2 T}{\partial z^2}\right)=\frac{1}{c\rho}p(r,z,\varphi,t), \tag{1}$$

where T – temperature;
λ – heat conductivity coefficient;
c – specific heat capacity;
ρ – material density;
t – current time;
r, z, φ – cylindrical coordinates.

The first part of the differential equation (1) $p(r, z, \varphi, t)$ is the power density of the energy source, which is the cause of the acoustic-magnetic device heating; i.e. power, referred to the transformer capacity. In general, the power density $p(r, z, \varphi, t)$ works as coordinates and time. Relationship between p and coordinates indicates that there is a source of heat in every spot of the volume and the energy is distributed unevenly in volume. In case of the acoustic magnetic device, the losses in the windings (losses in copper) and losses in the ferrite should be taken as a source of heat, but in the volume of the acoustic magnetic device they are distributed evenly, and at each point of the volume the same energy is released. Thus, further on we shall assume that the power density is independent of coordinates, but depends on time. The ohmic losses in the windings of the acoustic magnetic device are expressed by the following formula

$$P_M = r_1 i_1^2 + r_2 i_2^2, \tag{2}$$

where r_1, r_2 – ohmic resistance of the primary and secondary windings of the acoustic magnetic device;
i_1, i_2 – full-load current of the primary and secondary windings.

To experimentally observe the loss parameter in the acoustic magnetic device windings a short circuit test is performed. Thus, the acoustic magnetic device is turned into a two-terminal device connected to external circuits only by the primary winding terminals. Using the notion of effective resistance r_0, the formula (2) can look like:

$$P_M = r_0 i_1^2. \tag{3}$$

There can be found the following expression for calculating the reduced resistance in literature [8]:

$$r_0 = r_1 + n^2 r_2, \tag{4}$$

where n – VT ratio, provided that $n=\frac{i_2}{i_1}$, which is valid only if we ignore the magnetization of the magnetic circuit and the losses in ferrites.

The second group of losses in the acoustic magnetic device comprises the losses in the magnetic circuit. An estimate of the energy loss in the core (ferrite), which is accurate for practical purposes, can be obtained from the equivalent electrical scheme of core replacement, according to which the energy entering the core during the operating t_i is determined by the energy absorbed by the two branches of the scheme L_{st} and R_p:

- power, distributed in the core

$$W_p = \frac{U_m^2 t_i}{R_p} = \frac{\Delta B^2 Sl}{R_0 t_i}, \tag{5}$$

where U_m – amplitude of square wave;
S – cross-section of magnetic conductor;
ΔB – diference of induction;

R_p – resistance losses;
R_0 – given resistance losses;
l – lenght of central force line of core;
t_i – pulse length.

- magnetization energy, i.e. the energy transferred to load or accumulated in the ferrite

$$W_M = \frac{U_m^2 t_i^2}{2L_{st}} = \frac{\Delta B^2 Sl}{2\mu_0 \mu_\Delta} \quad , \tag{6}$$

where μ_0 – absolute magnetic permeability of vacuum;
μ_Δ – magnetic permeability of core in static mode;

After further conversion, we obtain the following expression for the energy value applied to the core (ferrite):

$$P_f = \frac{\Delta B^2 Sl}{2\mu_0 \mu_\Delta}(1 + \frac{2\tau_p}{t_i}), \tag{7}$$

where τ_p – time;

The total loss power is defined as the sum of losses in copper and losses in ferrite and is expressed by the formula:

$$P = r_0 i_1^2 + P_f . \tag{8}$$

Let us consider an acoustic magnetic device, in which the windings are made of copper wire. The resistance of the conductor used in the acoustic magnetic device is proportional to the difference in the ambient and wire temperatures. Taking this into account, we write down the total losses in the apparatus in the following way:

$$P = [1 + \chi(T - T_0)] r_0 i^2 + P_f , \tag{9}$$

where χ – temperature coefficient of resistance (TCR);
T_0 – ambient temperature;
T – acoustic magnetic device temperature.

In order to determine the right-hand side of the heat equation, it is necessary to plug the expression (1) into it, divided by the volume (V) of the acoustic magnetic device. Power density and loss density are denoted by lower case letters p, p_1, p_0 Coming from (9) it is:

$$p = [1 + \chi(T - T_0)] p_1 + p_0 , \tag{10}$$

where $p_0 = \frac{r_0 i^2}{V}$ and $p_1 = \frac{P_f}{V}$ – copper and ferrite loss density relatively.

Expression (10) determines the right-hand side of equation (2), which turns out to be temperature and time dependent. Returning to the problem of cooling the acoustic magnetic device, let us agree that heat transfer on the boundary of the surface of the acoustic magnetic device and the environment takes place according to the Newton's law. According to this law, the boundary conditions for the differential equation (1) have the form of:

$$\left[-\lambda \frac{\partial T}{\partial n} = \alpha (T - T_0) \right]_S , \tag{11}$$

where $\frac{\partial T}{\partial n}$ – normal derivative to the surface;
S – acoustic magnetic device surface area;
α – heat-exchange coefficient of the acoustic magnetic device with environment.

The heat exchange of the acoustic magnetic device with the surrounding environment occurs through the lateral and end surfaces. Therefore, in general, for the specification of the cooling conditions, it is necessary to introduce a coefficient of heat exchange for each surface of the acoustic-magnetic device. By varying the heat transfer coefficients, it is possible to simulate various cooling conditions for the acoustic magnetic device. The heat exchange of the acoustic magnetic device with the environment takes place through two lateral and two side surfaces. From the general interface condition (11), it is necessary to obtain interface conditions for each surface. For this it is necessary to take the derivative of the temperature flatwise. Let the acoustic magnetic device have the following geometric parameters: R_1 - internal radius, R_2 - outer radius, h - height. Then, for the inner lateral cylindrical surface of the acoustic magnetic device, on the basis of (3), we receive:

$$\begin{aligned} -\lambda\frac{\partial T}{\partial n} &= -\lambda n\cdot grad(T) = \\ &= -\lambda(-e_r)\cdot\left(\frac{\partial T}{\partial r}e_r + \frac{1}{r}\frac{\partial T}{\partial\varphi}e_\varphi + \frac{\partial T}{\partial z}k\right) = \lambda\left.\frac{\partial T}{\partial r}\right|_{r=R_1} = \alpha_1(T-T_0), \end{aligned} \tag{12}$$

where e_r, e_φ, k – cross-cut cylindrical coordinates system, and the point (.) means scalar product; α_1 – heat-exchange coefficient for the internal cylindrical surface of the acoustic magnetic device.

Using formula (11), we can write down the interface conditions for the side surface of the acoustic magnetic device:

$$\begin{aligned} -\lambda\frac{\partial T}{\partial n} &= -\lambda n\cdot grad(T) = \\ &= -\lambda(e_r)\cdot\left(\frac{\partial T}{\partial r}e_r + \frac{1}{r}\frac{\partial T}{\partial\varphi}e_\varphi + \frac{\partial T}{\partial z}k\right) = \lambda\left.\frac{\partial T}{\partial r}\right|_{r=R_2} = \alpha_2(T-T_0), \end{aligned} \tag{13}$$

where α_2 – heat-exchange coefficient for the side cylindrical surface of the acoustic magnetic device.

Setting the normal vector to the end surfaces of the acoustic magnetic device, from the general expression (11) we obtain the interface conditions on the end surfaces. On the lower end surface of the acoustic magnetic device with the coefficient of heat transfer α_3 we will have:

$$\begin{aligned} -\lambda\frac{\partial T}{\partial n} &= -\lambda n\cdot grad(T) = \\ &= -\lambda(-k)\cdot\left(\frac{\partial T}{\partial r}e_r + \frac{1}{r}\frac{\partial T}{\partial\varphi}e_\varphi + \frac{\partial T}{\partial z}k\right) = \lambda\left.\frac{\partial T}{\partial z}\right|_{z=0} = \alpha_3(T-T_0). \end{aligned} \tag{14}$$

For the upper end surface of the acoustic magnetic device, we obtain the following:

$$\begin{aligned} -\lambda\frac{\partial T}{\partial n} &= -\lambda n\cdot grad(T) = \\ &= -\lambda k\cdot\left(\frac{\partial T}{\partial r}e_r + \frac{1}{r}\frac{\partial T}{\partial\varphi}e_\varphi + \frac{\partial T}{\partial z}k\right) = -\lambda\left.\frac{\partial T}{\partial z}\right|_{z=h} = \alpha_4(T-T_0). \end{aligned} \tag{15}$$

In accordance with the earlier assumption, we determine the temperature of the acoustic magnetic device as the average temperature by capacity:

$$\Theta = \frac{1}{V}\int_V Trdrdzd\varphi. \tag{16}$$

Interface conditions (11) for average temperature are rewritten as follows:

$$\lambda\left.\frac{\partial T}{\partial z}\right|_{z=0} = \alpha_3(\Theta-T_0);\ -\lambda\left.\frac{\partial T}{\partial z}\right|_{r=R_2} = \alpha_2(\Theta-T_0),$$

$$-\lambda \frac{\partial T}{\partial z}\bigg|_{z=h} = \alpha_4(\Theta - T_0);\ \lambda \frac{\partial T}{\partial z}\bigg|_{r=R_1} = \alpha_1(\Theta - T_0). \tag{17}$$

Volume integral of heat conductivity equation (1):

$$\frac{1}{V}\int_V \frac{\partial T}{\partial t} rdrdzd\varphi = \frac{\lambda}{c\rho}\frac{1}{V}\left(\int_V \frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)drdzd\varphi + \right. \\ \left. + \int_V \frac{\partial^2 T}{\partial z^2} rdrdzd\varphi\right) + \frac{1}{c\rho}\frac{1}{V}\int_V prdrdzd\varphi. \tag{18}$$

If integrate over the thermal conductivity in volume with due account for $\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\left(\frac{\partial T}{\partial r}\right) = \frac{1}{r}\left(\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)\right)$ and allowance, the temperature of the acoustic magnetic device does not depend on the angular coordinate φ because of the obvious symmetry of the algorithm:

In the first integral (18) we interchange the operations of differentiation and integration, and also use the definition of the average temperature (16). As a result, we get:

$$\frac{1}{V}\int_V \frac{\partial T}{\partial t} rdrdzd\varphi = \frac{\partial}{\partial t}\left(\frac{1}{V}\int_V Trdrdzd\varphi\right) = \frac{\partial \Theta}{\partial t}. \tag{19}$$

The second addendum in (18) can be integrated with respect to the variable r from R_1 to R_2. After integration, the second addendum of eq. (18) can be transformed into an integral over the lateral surface of the acoustic magnetic device and takes the following form:

$$\frac{\lambda}{c\rho}\frac{1}{V}\left(\int_V \frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right)drdzd\varphi\right) = \frac{1}{c\rho}\frac{1}{V}\left(\int_{S_b} r\lambda \frac{\partial T}{\partial r}\bigg|_{R_2}^{R_1} dzd\varphi\right). \tag{20}$$

Substituting the interface conditions from (17) into (20), after integration we obtain:

$$\frac{1}{c\rho V}\left(\int_{S_b} r\lambda \frac{\partial T}{\partial r}\bigg|_{R_2}^{R_1} dzd\varphi\right) = -\frac{2\pi h(\alpha_1 R_1 + \alpha_2 R_2)}{c\rho V}(\Theta - T_0). \tag{21}$$

The third addendum of eq. (18) after integrating over the volume and taking into account the interface conditions (17) takes the form of:

$$\frac{\lambda}{c\rho V}\left(\int_V \frac{\partial^2 T}{\partial z^2} rdrdzd\varphi\right) = \frac{\pi(\alpha_3 + \alpha_4)(R_1^2 - R_2^2)}{c\rho V}(\Theta - T_0). \tag{22}$$

In the right-hand side of equation (18) we substitute the power density from (10):

$$\frac{1}{c\rho}\frac{1}{V}\int_V prdrdzd\varphi = \frac{1}{c\rho}\frac{1}{V}\int_V \left[p_0 + p_1 + \chi(T - T_0)p_1\right] rdrdzd\varphi. \tag{23}$$

After integrating (23) with regard to (16), we obtain:

$$\frac{1}{c\rho}\frac{1}{V}\int_V \left[p_0 + p_1 + X(T - T_0)p_1\right] rdrdzd\varphi = \\ = \frac{p_0 + p_1 + \chi(\Theta - T_0)p_1}{c\rho}. \tag{24}$$

The resulting expressions (19), (21), (22), and (24) are put in equation (18), then we have:

$$\frac{\partial \Theta}{\partial t} = \frac{f}{c\rho V}(\Theta - T_0) + \frac{p_0 + p_1 + \chi(\Theta - T_0)p_1}{c\rho}, \tag{25}$$

where f parameter is introduced to shorten the record:

$$f = 2\pi h(\alpha_1 R_1 + \alpha_2 R_2) + \pi(\alpha_3 + \alpha_4)(R_2^2 - R_1^2). \tag{26}$$

We reduce equation (25) to the normal form:

$$\frac{\partial(\Theta - T_0)}{\partial t} = -\frac{(\Theta - T_0)}{c\rho}\left(\frac{f}{V} - \chi p_1\right) + \frac{p_0 + p_1}{c\rho}. \tag{27}$$

Thus, for the superheat temperature of the transformer, an ordinary differential equation with constant coefficients (27) is obtained. We integrate equation (27) under the initial conditions

$$\Theta(0) = T_0, \tag{28}$$

then we receive:

$$\Theta - T_0 = \frac{Vp_0 + Vp_1}{f - \chi V p_1}(1 - e^{-\frac{t}{\tau}}), \tag{29}$$

where

$$\tau = \frac{c\rho V}{f - \chi V p_1}. \tag{30}$$

Thus, we introduce a tag for the mass of the acoustic magnetic device $M = \rho V$, by rewriting (30) in the following form:

$$\tau = \frac{cM}{f - \chi V p_1}. \tag{31}$$

We use the average value of the heat capacity in calculations, which is determined by formula:

$$c = \frac{c_m m_M + c_n m_n + \sum c_i m_i}{m_M + m_n + \sum m_i}, \tag{32}$$

where c_m, c_n, c_i – heat capacity of copper, polyethylene and other materials,
m_M, m_n, m_i – mass of copper, polyethylene and other materials.

The value of the average heat capacity affects only the parameters of the heating process and does not affect the value of the steady-state temperature.

Taking into account that $V_{p1} = r_0 i^2$ and $V_{p0} = P_f$ the formula for calculating the superheat temperature of the acoustic magnetic device (29) and the expression for the time τ, we transform it to the form:

$$\Theta - T_0 = \frac{r_0 i_1^2 + P_f}{f - \chi r_0 i_1^2}(1 - e^{-\frac{t}{\tau}}), \tag{33}$$

$$\tau = \frac{cM}{f - \chi r_0 i_1^2}. \tag{34}$$

Formula (33) makes it possible to evaluate the dynamics of heating and determine the steady-state superheat temperature of the acoustic magnetic device.

Then, calculating the limit (33), if $t \to \infty$ we obtain the expression for the steady-state superheat temperature in the following form:

$$\Theta - T_0 = \frac{r_0 i_1^2 + P_f}{f - \chi r_0 i_1^2}. \tag{35}$$

Equation (35) shows that for a constant load and after a sufficiently long time, the acoustic magnetic device heats up to Θ = const temperature.

Since it is not known in advance what the factors are and how it will affect the values of the heat transfer coefficients in the specific operating conditions of the acoustic magnetic device, it is logical to assume that the conditions for cooling the acoustic magnetic device are the same over the entire surface and all the heat exchange coefficients are equal to each other:

$$\alpha_1 = \alpha_2 = \alpha_3 = \alpha_4 = \alpha_0. \quad (36)$$

Substituting (36) into (26) and rearranging the terms in (26), we get:

$$f = \alpha_0 \left[2\pi (R_2^2 - R_1^2) + 2\pi h (R_1 + R_2) \right]. \quad (37)$$

We shall rewrite the formula (37) as:

$$f = \alpha_0 F_0, \quad (38)$$

where $F_0 = 2\pi (R_2^2 - R_1^2) + 2\pi h (R_1 + R_2)$ – toroid surface area, through which the heat exchange with the environment is performed.

Taking into account (38), the final equation for the steady-state superheat temperature of the acoustic magnetic device is written in the form of:

$$\theta - T_0 = \frac{r_0 i^2 + P_f}{\alpha_0 F_0 - \chi r_0 i^2}. \quad (39)$$

It would be more convenient to replace the surface area of the acoustic magnetic device by the surface area of the magnetic circuit, which is easily calculated through its dimensions. For this, it is necessary to put forward a hypothesis, and then test it experimentally that the ratio of the areas of the surface of the device and the magnetic circuit is constant and does not depend on the power of the acoustic magnetic device. Formally, this statement can be written in the following form:

$$k_F = \frac{F_0}{F}, \quad (40)$$

where F – magnetic circuit surface area;
k_F – additional coefficient.

Expressing from (40) the surface area of the acoustic magnetic device and substituting it in (39), we obtain:

$$\theta - T_0 = \frac{r_0 i^2 + P_f}{k_F \alpha_0 F - \chi r_0 i^2}. \quad (41)$$

We introduce the generalized coefficient of heat transfer as $\alpha = k_F \alpha_0$, then for the steady-state superheat temperature of the acoustic magnetic device we obtain the final expression [9]:

$$\theta - T_0 = \frac{r_0 i^2 + P_f}{\alpha F - \chi r_0 i^2}, \quad (42)$$

where r_0 – impedance of the device;
χ – temperature coefficient of resistance;
i – total value of the device current;
θ – average temperature in the volume of the device;
T_0 – ambient temperature;
$r_0 i^2 + P_f$ – total power of losses;
P_f – loss in the magnetic circuit.

To prove the stated hypothesis the following solution was made in the ELCUT 6.1.

The first step is to create a problem such as the “Magnetic field of alternating currents” in the ELCUT 6.1 environment. Having established the properties of the problem, we proceed to the construction of the geometric model of the device [10]. The diagram of the device is presented in a section for more graphic representation of the magnetic field pattern. Figure 1 shows a geometric model in the ELCUT 6.1 environment.

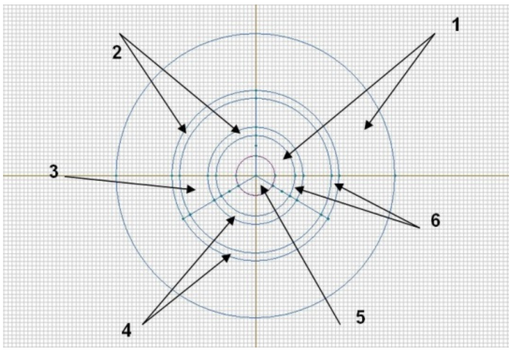

Fig. 1. **Geometric model in ELCUT 6.1 environment** : 1 – body of the device; 2 –first winding; 3 –ferrite ring; 4 –second winding; 5 –working zone; 6 –third winding

Following the creation of the geometric model of the problem, the physical properties of objects, as well as the boundary conditions, are specified with the help of marks. One winding is 120 ° from the circle of the ferrite ring. The frequency at which the device is simulated is 18 kHz. The choice of precisely this frequency is due to the fact that at the given frequency the ferrite ring enters resonance [11]. Then an electrical circuit is created to power the device.

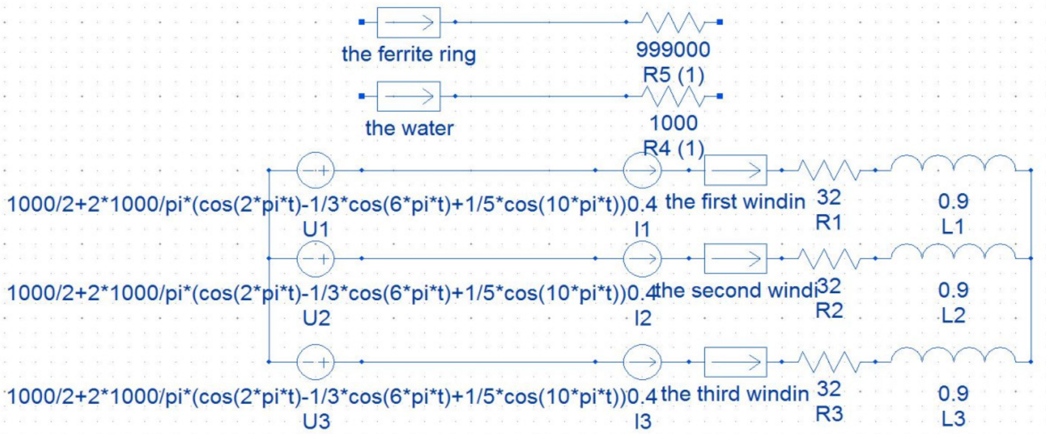

Fig. 2. **Electrical circuit in environment of ELCUT 6.1 signal form of square waves**

Next, a finite element mesh is constructed in all the used parts of the geometric model, with a discretization step of 0.5. The geometric model allows to specify physical properties of objects and boundary conditions [12].

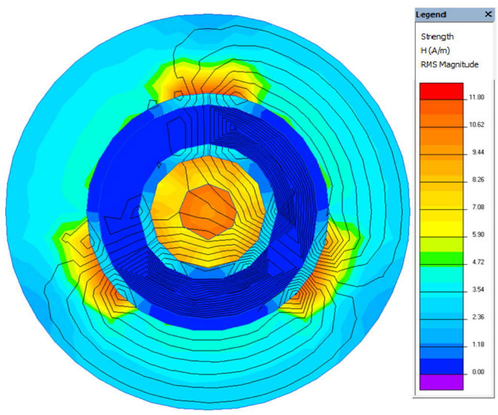

Fig. 3. **Distribution of maximum tension applying voltage of meander type**

Figure 3 shows the magnetic field pattern, when voltage of the meander type is applied to the device. It is necessary to find the laws for distribution of temperature both inside and on the surface of the device under long-term operating conditions, since incomplete use of heating possibilities leads to a low-power electromagnetic field and to deterioration of magnetic processing, and overheating leads to destruction of interlayer insulation and turn-to-turn short circuit. In addition, it is necessary to know the value of the temperature inside the pipeline, through which the processed substance passes, since in acoustic magnetic treatment of certain substances the temperature limits are strictly set, non-observance of which leads to unsatisfactory results.

To obtain a complete picture of the thermal field it is necessary to take into account the solution of the problem of analyzing the magnetic field and the acoustic field. To simulate the heat transfer process, the ambient temperature is set at 283 °K, and the water temperature inside the pipeline is 361 °K.

The pattern of the temperature distribution over the acoustic magnetic apparatus taking into account the heating at the boundary of the external and internal media is shown in Fig. 4.

Since the heat flow passes through the inhomogeneous body of the toroidal magnetic circuit, air gaps, interlayer and coil insulation and wire metal, the thermal field of the apparatus is very complex, so an equivalent thermal conductivity was used to simplify the solution of the problem.

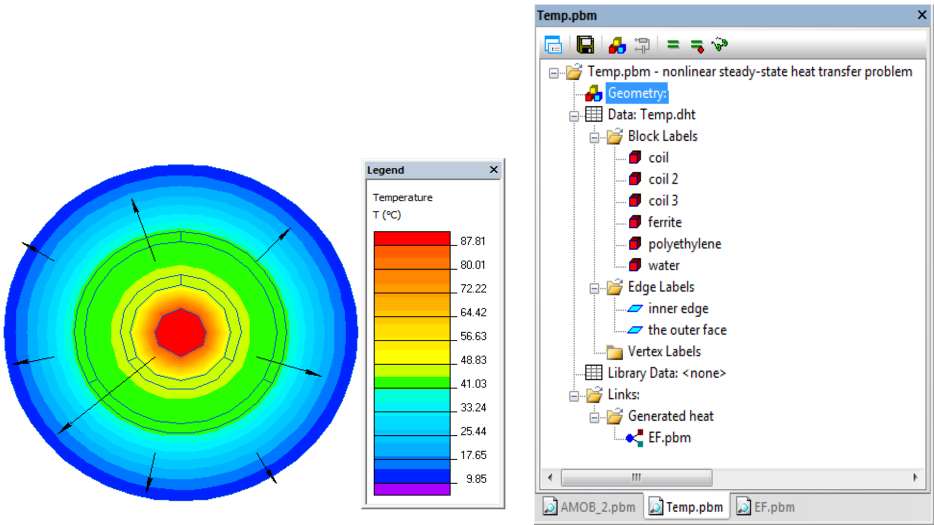

Fig. 4. **Temperature distribution in operating mode and nonlinear steady-state heat transfer problem**

Results and discussion

On the basis of the theoretical studies and modelling, a model of the device was made and its testing confirmed the theoretical studies. The studies confirmed the maximum efficiency of the application of the pulse voltage supply of the acoustic magnetic device of the "meander" form. Figure 5 shows the acoustic magnetic device installed in a geothermal boiler house.

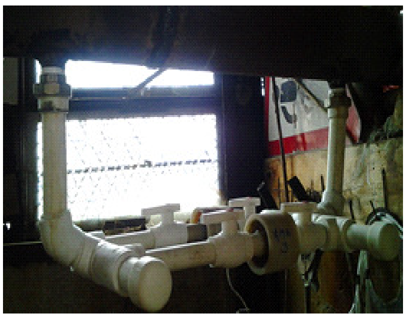

Fig. 5. **Exterior of devices installed on pipes in boiler room**

Figure 6 shows the device installed at the exit of a geothermal well, which was calculated in accordance with the model created.

Fig. 6. **Exterior of tube supplying geothermal water and device with electronic components installed on it**

The efficiency of the device was tested during the year of its operation. As a result of routine maintenance it was found that the amount of deposits on the pipes began to tend to zero. Figure 7 shows a damper that has been used throughout the heating season.

Before installing the device, the dampers were discarded after two weeks of operation. Traditionally, magnetic devices are used for treatment of water and solution. The device's parameters are: conditional diameter (mm): 80; 100; 200; 600; nominal pressure (mPa): 1.6; capacity of processed water ($m^3 \cdot h^{-1}$): 25-600; magnetic field strength ($kA \cdot m^{-1}$): 200; consumed power by electromagnet (kW): 0.35-1.8; dimensions of magnet (mm): 260×420; 440×835; 520×950; 755×1100; weight of magnet (kg): 40; 200; 330; 1000.

Fig. 7. **Damper in disassembled form after heating season with device**

Ten of these devices installed on a pipe with a diameter of 80 mm demonstrate the power consumption 1.5 kW, weight – 40 kg. With the installation of ten acoustic and magnetic devices (Figure 6), the power consumption is 70-100 watts, weight – 8 kg. However, the performance for the processed water is the same (25 $m^3 \cdot h^{-1}$). The measured value of the magnetic field strength of the acoustic and magnetic device in the working area is 15 $A \cdot m^{-1}$ with RMS = 1. It is planned to optimize the overall dimensions and power of the device.

Conclusions

According to the temperature field modeling it can be concluded that the superheating temperature of the acoustic magnetic device has acceptable limits, which allows to produce optimal treatment of geo-thermal water for a long time in an accident-free state without using a forced cooling system. Since the effect of acoustic magnetic water treatment is not long in time, the state of constant water treatment allows to maintain the pressure in the pipes within the operating limits in the inter regulation period and thus to save the energy consumption. Using polyethylene as a material of the acoustic magnetic device body, ferrite core of the acoustic magnetic device, shape of the signal type meander and reducing the heating of the acoustic magnetic device windings allow to optimize reagentless treatment of geothermal water.

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