METHODS FOR DETERMINING OPTIMAL CHARACTERISTICS OF ACOUSTIC-MAGNETIC DEVICES INSTALLED ON GREENHOUSE GEOTHERMAL HEATING SYSTEM PIPES OF VARIOUS DIAMETERS

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Abstract. There is a problem of installation of acoustic-magnetic devices at pipes of various diameters, when planned routine pipe replacement work is carried out in greenhouse geothermal heating systems. This technical problem determines a scientific problem of finding acoustic-magnetic devices characteristics, which allow to change only the acoustic-magnetic device internal diameter, if transition to different pipe diameter is needed. To solve this problem, a hypothesis was put forward about the possibility of finding the extremes of the function of water treated with physical field salts separation process. For the hypothesis of the experimental study an acoustic-magnetic model of the device was studied. This model represents the relationship between the following factors: the size of the ring, the inner diameter of the pipe, similarity coefficients, and the resulting variable – the antiscale effect. It was decided to study the optimum region by screening out insignificant factors and building a plan for the 2ndcomplete factor experiment. After translating significant similarity coefficients into natural values and analyzing the physical quantities dimensions, physical regularities of phenomena were revealed by means of functional dependencies between the quantities. When implementing the planning matrix, an inadequate model was obtained. Using the steep ascent method, it was not possible to obtain the optimization parameters, so it was decided to build a second order orthogonal plan to describe the optimum area. The second order regression equation turned out to be adequate. Its extremum was found. To verify the obtained global maximum values of the geothermal water acoustic-magnetic treatment process, the function value was calculated from the model. The results allowed to obtain the optimal efficiency of preventing scale formation on the greenhouse complex geothermal heating system pipes of various diameters by the optimal characteristics of the acoustic-magnetic devices.

Keywords: acoustic-magnetic devices, heating system, orthogonal plan, regression equation, optimal efficiency, optimum region.

Introduction

The use of energy resources is associated with high costs for development, transportation, labor and environmental protection. Depletion of energy resources is a tendency all over the world; therefore many countries are considering various energy sources, although some of them can meet only a small proportion of energy needs. Geothermal energetics develops rapidly in the United States [1], Mexico, Italy, Japan, and Russia. 66 geothermal fields have been explored in Russia (Kamchatka, Kurile Islands, West-Siberian and North Caucasus regions), and more than 4 000 boreholes have been drilled for the use of geothermal resources. These fields are capable to generate near to 10 000 MW of heat and 200 MW of electricity. For example, geothermal deposits have been developed at the depth from 300 to 5000 m (water temperature reaches 180 ºC) in the North Caucasus region [2].

Less than 5 % of the geothermal heat supply system potential is used in geothermal heat supply systems. [3,4]. Greenhouses in the south of Russia using the geothermal energy, experience an acute problem of scale formation on the internal surfaces of the heat supply system equipment. High salt concentration leads to high intensive process of scale formation, on account of that heat transfer is decreased or heating equipments fail. These problems may be solved by water treatment with an acoustic-magnetic device, but it is necessary to find the optimal parameters of the acoustic-magnetic devices installed on pipes of various diameters for optimal efficiency of geothermal water treatment. To solve the scientific problem, a hypothesis is put forward on the possibility of finding the optimal parameters of acoustic magnetic devices, installed on pipes of various diameters, for optimal efficiency of processing geothermal water.

Materials and methods

The process of extracting salts from water treated with physical fields can be represented as a dependency:

$$\xi_{ra} = f(P_1, P_2, P_3),$$

where P_1 – number of wire turns of one phase of the device;
P_2 – frequency of the voltage applied to the acoustic-magnetic device;
P_3 – voltage applied to the acoustic-magnetic device.

Anti-scale effect is used as the optimization parameter. It directly determines the efficiency of liquid treatment in a heat supply system. Its value is defined as:

$$\theta = \frac{M_O - M_H}{M_O}, \tag{1}$$

where M_H – mass of solid deposits on the plate during the experiment (for treated geothermal water);
M_0 – mass of solid deposits on the plate during the experiment (for untreated geothermal water).

The levels of factor variation and parameter encoded designations [5] of the acoustic-magnetic device are presented in Table 1.

Table 1

Levels and encoded designations of experiments

Top level (+)	1220	29100	36
Base level (0)	915	27500	24
Bottom level (–)	610	25900	12
Code designation	P_{n1}	P_{n2}	P_{n3}

The encoded factors have the form:

$$P'_{n1} = \frac{P_{n1} - P_{n1(0)}}{\Delta P_1} = \frac{P_{n1} - 915}{305};\; P'_{n2} = \frac{P_{n2} - P_{n2(0)}}{\Delta P_2} = \frac{P_{n2} - 27500}{1600};\; P'_{n3} = \frac{P_{n3} - P_{n3(0)}}{\Delta P_3} = \frac{P_{n3} - 24}{12}. \tag{2}$$

The study of the optimum area is presented in Table 2.

Table 2

Resulting and factorial characteristics for a linear model

Experiments	**Encoded designations**					
	P'_{n1}	P'_{n2}	P'_{n3}	ξ_{ra1}	ξ_{ra2}	$\xi_{ra} = (\xi_{ra1} + \xi_{ra2})/2$
1	(–)	(–)	(–)	0.830	0.870	0.85
2	(+)	(–)	(–)	0.868	0.892	0.88
3	(–)	(+)	(–)	0.921	0.939	0.93
4	(+)	(+)	(–)	0.964	0.976	0.97
5	(–)	(–)	(+)	0.908	0.912	0.91
6	(+)	(–)	(+)	0.923	0.917	0.92
7	(–)	(+)	(+)	0.865	0.915	0.89
8	(+)	(+)	(+)	0.700	0.990	0.98

The results obtained in the experiment are used to form the linear model:

$$\xi_{ra} = 0.916 + 0.02425 P'_{n1} + 0.02625 P'_{n2} + 0.00875 P'_{n3}. \tag{3}$$

The statistical analysis of the results of the experiment did not reveal the homogeneity of the dispersion of the experiments. When implementing the planning matrix, an inadequate model was obtained, because the value of Fisher's criterion is [6]:

$$F_{\text{calculated}} = \frac{S^2_{\text{yremains}}}{S^2_{\xi_{\text{ra}}}} = \frac{0.00096}{0.00017} = 5.6 \geq F_{\alpha;n-l,n-1} = 4.37, \tag{4}$$

where $F_{\alpha;n-l,n-1} = 4.37$ – critical value of Fisher's distribution found from table.

The optimization parameters could not be obtained during a steep ascent, therefore, the decision was made to build a second-order plan to describe the optimum area. In order to do this, the orthogonal plan of the second order is used. The results of the experiments presented in Table 2 were used as the core of planning. In order to complete the existing plan to the second order plan, experiments were conducted at a distance from the center and at the zero level. The data for determining the experience conditions are presented in Table 3.

Table 3

Data for determining the conditions of the experiment

Basic level	2745	27500	24
Star points			
- *d* (-1.215)	1633.4	25556	9.42
+ *d* (1.215)	3856.8	29444	38.58
Encoded designations	P_{n1}	P_{n2}	P_{n3}

The values of regression coefficients are determined with the results of experiments

$$\beta_0 = \frac{\sum_{u=1}^{N} \xi_{ra}}{N} = 0.927, \beta_1 = \frac{\sum_{u=1}^{N} \xi_{ra} P'_{n1u}}{10.9544} = 0.004, \beta_2 = \frac{\sum_{u=1}^{N} \xi_{ra} P'_{n2u}}{10.9544} = 0.015, \beta_3 = \frac{\sum_{u=1}^{N} \xi_{ra} P'_{n3u}}{10.9544} = 0.048$$

$$\beta_{11} = \frac{\sum_{u=1}^{N} \xi_{ra} P'^2_{n1u}}{4.364} = -0.017, \beta_{22} = \frac{\sum_{u=1}^{N} \xi_{ra} P'^2_{n2u}}{4.364} = -0.007, \beta_{33} = \frac{\sum_{u=1}^{N} \xi_{ra} P'^2_{n3u}}{4.364} = -0.017, \quad (6)$$

$$\beta_{12} = \frac{\sum_{u=1}^{N} \xi_{ra} P'_{n1u} P'_{n2u}}{8} = -0.009, \beta_{13} = \frac{\sum_{u=1}^{N} \xi_{ra} P'_{n1u} P'_{n3u}}{8} = -0.005, \beta_0 = \frac{\sum_{u=1}^{N} \xi_{ra}}{N} = 0.927.$$

The equation has the following form:

$$\xi_{ra} = 0.927 + 0.004 P'_{n1} + 0.015 P'_{n2} + 0.048 P'_{n3} - 0.009 P'_{n1} P'_{n2} + 0.005 P'_{n1} P'_{n3} + 0.013 P'_{n2} P'_{n3} - \\ - 0.017 (P'^2_{n1} - \frac{11}{15}) - 0.007 (P'^2_{n2} - \frac{11}{15}) - 0.017 (P'^2_{n3} - \frac{11}{15}) \quad . (7)$$

According to:

$$\tilde{\beta}_0 = 0.927 - \frac{11}{15}(-0.017 - 0.007 - 0.017) = 0.957$$

this equation is simplified:

$$\xi_{ra} = 0.957 + 0.004 P'_{n1} + 0.015 P'_{n2} + 0.048 P'_{n3} - 0.009 P'_{n1} P'_{n2} + 0.005 P'_{n1} P'_{n3} + 0.013 P'_{n2} P'_{n3} - \\ - 0.017 (P'^2_{n1}) - 0.007 (P'^2_{n2}) - 0.017 (P'^2_{n3}). \quad (8)$$

In order to check the adequacy of the model (8) with *F*– criterion (Fischer's criterion), it is necessary to calculate the variance by $S^2_{\xi_{ra}}$ (total variance) and S^2_{yremains} (remainder variance) (9):

$$S^2_{\xi_{ra}} = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \bar{y}_i)^2; \; S^2_{\text{yremains}} = \frac{1}{n-1} \sum_{i=1}^{n} (y_i - \tilde{y}_i)^2, \quad (9)$$

where n – number of experiments;
$l = k + 1$ – number of terms of the approximating polynomial;
k – number of factors.

Value of the Fisher's criterion is equal to:

$$F_{\text{calculated}} = \frac{S^2_{\text{yremains}}}{S^2_{\xi_{ra}}} = \frac{0.0044}{0.0024} = 1.83 \le F_{(0.05; f_1; f_2)} = 6.256, \quad (11)$$

thus, the model is adequate to the experimental data.

Table 4

Conditions and results of experiments based on the plan of the second order

No.	P'_{n0}	P'_{n1}	P'_{n2}	P'_{n3}	$P'_{n1} P'_{n2}$	$P'_{n1} P'_{n3}$	$P'_{n2}P'_{n3}$	$(P'_{n1})^2$ -11/15	$(P'_{n2})^2$ -11/15	$(P'_{n3})^2$ -11/15	ξ_{ra}
1	+1	-1	-1	-1	+1	+1	+1	4/15	4/15	4/15	0.89
2	+1	+1	-1	-1	-1	-1	+1	4/15	4/15	4/15	0.87
3	+1	-1	+1	-1	-1	+1	-1	4/15	4/15	4/15	0.82
4	+1	+1	+1	-1	+1	-1	-1	4/15	4/15	4/15	0.86
5	+1	-1	-1	+1	+1	-1	-1	4/15	4/15	4/15	0.95
6	+1	+1	-1	+1	-1	+1	-1	4/15	4/15	4/15	0.98
7	+1	-1	+1	+1	-1	-1	+1	4/15	4/15	4/15	0.96
8	+1	+1	+1	+1	+1	+1	+1	4/15	4/15	4/15	0.99
9	+1	-1.215	0	0	0	0	0	23/30	-11/15	-11/15	0.95
10	+1	+1.215	0	0	0	0	0	23/30	-11/15	-11/15	0.92
11	+1	0	-1.215	0	0	0	0	-11/15	23/30	-11/15	0.94
12	+1	0	+1.215	0	0	0	0	-11/15	23/30	-11/15	0.96
13	+1	0	0	-1.215	0	0	0	-11/15	-11/15	23/30	0.89
14	+1	0	0	+1.215	0	0	0	-11/15	-11/15	23/30	0.98
15	+1	0	0	0	0	0	0	-11/15	-11/15	-11/15	0.95

It is necessary to find the extremum of the function (9) on the set $P_m^{\,n}$. The necessary conditions of the extremum are [7]:

$$\begin{cases} \dfrac{\partial f}{\partial P'_{n_1}} = 0.004 - 0.034P'_{n_1} - 0.009P'_{n_2} + 0.005P'_{n3} = 0; \\ \dfrac{\partial f}{\partial P'_{n2}} = 0.015 - 0.009P'_{n_1} - 0.014P'_{n_2} + 0.013P'_{n3} = 0; \\ \dfrac{\partial f}{\partial P'_{n_3}} = 0.048 + 0.005P'_{n_1} + 0.013P'_{n_2} - 0.034P'_{n3} = 0. \end{cases} \quad (12)$$

The result of solving this system is the stationary point:

$$P'_{n_1} = -0.546; P'_{n_2} = 4.122; P'_{n3} = 2.908. \quad (13)$$

The second partial derivatives of f are equal to:

$$\frac{\partial^2 f}{(\partial P'_{n_1})^2} = 0.034; \frac{\partial^2 f}{\partial P'_{n_1}\partial P'_{n_2}} = \frac{\partial^2 f}{\partial P'_{n_2}\partial P'_{n_1}} = 0.009; \frac{\partial^2 f}{\partial P'_{n_1}\partial P'_{n_3}} = \frac{\partial^2 f}{\partial P'_{n_3}\partial P'_{n_1}} = 0.005;$$
$$\frac{\partial^2 f}{(\partial P'_{n_2})^2} = 0.014; \frac{\partial^2 f}{\partial P'_{n_2}\partial P'_{n_3}} = \frac{\partial^2 f}{\partial P'_{n_3}\partial P'_{n_2}} = 0.013; \frac{\partial^2 f}{(\partial P'_{n_3})^2} = 0.034. \quad (14)$$

We verify that the sufficient and necessary conditions for the extremum are satisfied. The Hessian matrix has the form:

$$H(\xi) = \begin{pmatrix} -0.034 & -0.009 & 0.005 \\ -0.009 & -0.014 & 0.013 \\ 0.005 & 0.013 & -0.034 \end{pmatrix}.$$

The sufficient extreme conditions are executed (all major minors of even order are non-negative, and all minors of odd order are not positive):

$$\Delta_1 = \ -0.034 < 0;$$

$$\Delta_2 = \begin{vmatrix} -0.034 & -0.009 \\ -0.009 & -0.014 \end{vmatrix} = 3.27 \cdot 10^{\ 4} > 0;$$

$$\Delta_3 = \begin{vmatrix} -0.034 & -0.009 & 0.005 \\ -0.009 & -0.014 & 0.013 \\ 0.005 & 0.013 & -0.034 \end{vmatrix} = \ 8.504 \cdot 10^{\ 6} < 0. \quad (15)$$

There is a maximum at the stationary point P

$$(P'_{n_1} = -0.546; P'_{n_2} = 4.122; P'_{n3} = 2.908).$$

The natural values of the factors are found from the relations:

$$P_{n_1} = P'_{n_1} \cdot 305 + 915 = 748.477; P_{n_2} = P'_{n_2} \cdot 1600 + 27500 = 34100; P_{n_3} = P'_{n_3} \cdot 12 + 24 = 58.9. \quad (16)$$

The extremum is reached at the point P, the value of the function is calculated according to model (8):

$$\begin{aligned} \xi_{n_1} &= 0.957 + 0.004 \cdot (-0.546) + 0.015 \cdot 4.122 + 0.048 \cdot 2.908 - 0.009 \cdot (-0.546) \cdot 4.122 + \\ &0.005 \cdot (-0.546) \cdot 2.908 + 0.013 \cdot 4.122 \cdot 2.908 - 0.017 \cdot (-0.546)^2 - 0.007 \cdot (4.122)^2 - \\ &0.017 \cdot (2.908)^2 = 1.057. \end{aligned} \quad (17)$$

It is necessary to transform the equation (9) to the canonical form by means of the coordinate axis rotation around the center. The angle of rotation of the coordinate axis is found from formula:

$$\mathrm{tg}\, 2\alpha = \frac{\beta_{12}}{\beta_{11} - \beta_{22}} = \frac{-0.009}{-0.017 - (-0.007)} = 0.9, \quad (18)$$

where α – angle of rotation of the axes.

If the sign of the rotation angle is negative, then the axes are rotated clockwise, and if it is positive, it is vice versa. Regression coefficients in canonical form are determined from the formula:

$$\begin{aligned} B_{11} &= \beta_{11} \cos^2 \alpha + \beta_{12} \cos\alpha \cdot \sin\alpha + \beta_{22} \sin^2 \alpha = -0.019; \\ B_{22} &= \beta_{11} \sin^2 \alpha + \beta_{12} \cos\alpha \cdot \sin\alpha + \beta_{22} \cos^2 \alpha = -6.091 \cdot 10^{-3}; \\ B_{22} &= 2(\beta_{22} - \beta_{11}) \sin \ \alpha \cdot \cos\alpha + \beta_{12} \cos 2\alpha = 0. \end{aligned} \quad (19)$$

To construct two-dimensional cross-section lines the equation is used:

$$\frac{P_1^2}{2.296} + \frac{P_2^2}{7.060} = 1. \quad (20)$$

The points of the cross-section curves are found with the standard equation.

Results and discussion

The test stand was designed and constructed for the experimental study of the acoustic-magnetic device installed at pipes of various diameters in greenhouse geothermal heating systems. The test stand (Fig.1) is an imitation of a closed heat supply system. There is an electric pump combined with a heating element in one case, a sludge collector, a circulation pump, and an electric ball valve at the test stand. The water flow is controlled by a controller.

The work of the stand is carried out in the following way: water is poured through a funnel into the experimental installation and pumped in the block combined with a circulation pump, from the sump enters the heating battery, passes through the electric ball valve, the acoustic-magnetic device and enters the reverse valve of the battery. The speed of water movement is changed by the electric ball valve. Passing the heating element, water is heated to the temperature of 70-80 ºC. Water heated to the necessary temperature (inside the unit of the combined pump and heating element, a temperature sensor is installed, configured to operate at a temperature of 70 ºC), enters the sludge collector, and then through the heating device, the settling tank with the element under study (a slide on which scale is formed). The waste water is drained into a container.

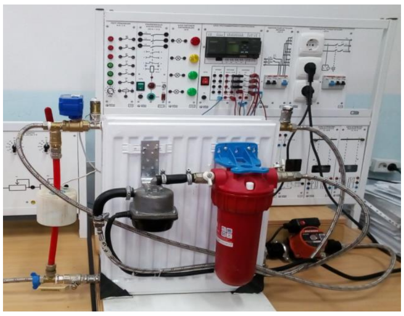

Fig. 1. **General view of the experimental setup for determining the efficiency of the acoustic-magnetic water treatment device**

The scale that has been removed from the inner wall of the battery settles in the lower part of the sludge collector (sump). Thus, the released suspension (sludge) that has passed the device and the battery settles in the sludge collector (sump) on the metal plate. After the experiment, the slide is examined under a microscope, which determines the amount of solid phase released. There is a general overview of geothermal heating and cooling systems in [8]. The works [10-12; 14] provide an extensive overview of new trends and modern approaches to the practical implementation of magnetic treatment of water to remove scale salts in heat exchangers and pipelines.

Conclusions

1. The test stand was designed and constructed in order to support the necessary process parameters, because it allows to install various acoustic-magnetic devices.
2. Series of experiments in accordance with the first-order plan were conducted. However, the obtained first-order model was not adequate, therefore the first-order plan was completed with “star” points to the second-order plan. Series of experiments were conducted, and an adequate second-order model was obtained. The optimal values of the acoustic-magnetic device parameters were obtained.
3. The results allow to obtain the optimal efficiency of preventing scale formation on greenhouse complex geothermal heating system pipes of various diameters by the optimal characteristics of acoustic-magnetic devices.
4. The following optimal parameters of the acoustic-magnetic device were found. The number of turns of one phase of the device is 749; the frequency of voltage applied to the device is 34.1 kHz; the voltage applied to the device is 59 V.

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