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INVESTIGATION OF THE INFLUENCE OF THE MODES OF THE OPERATION OF A GEOTHERMAL WELL WITH THE SYSTEMS OF HEAT SUPPLY AND AIR CONDITIONING IN COMBINATION WITH A THERMAL PUMP ON THE TEMPERATURE OF A SOIL LAYER

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Statement of the problem. We discuss the problem of the influence of the operation modes of the heat supply and conditioning systems in combination with the heat pump on the temperature of the soil massif and the development of a methodology for improving the design of these systems taking into account the long-term operation of the heat pump system from a low-potential heat source in a cyclic mode using criteria dependencies for the calculation of well operation parameters.
Results. A description is given of the change in the temperature of the reservoir of the soil massif under the operating conditions of the heat pump in two modes: only for heat supply and alternating heat supply / cooling (air conditioning) for 5 years.
Conclusions. A decrease in the temperature head in the bottomhole part of the geothermal well is revealed, which is used as an unconventional heat source in heat supply and conditioning systems caused by non-stationary thermal loads determined by climatic conditions.

Keywords: heat pump, temperature field, design method, criteria equations.

Introduction. Geothermal heat cannot be commonly used in most settled areas due to small background densities of heat flows. The use of heat pumps for selecting heat of geothermal wells is the solution, but previous experience of operating existing wells shows that technical and economic characteristics of well degrade during operation. Despite that there are still no comprehensible methods in place that would consider these changes [1, 3—5, 8, 10]. Therefore there have been some studies to address long-term prediction of changes in the parameters of geothermal wells operating in heat supply and air conditioning systems and those relying on cyclic changes in these systems.

1. Modeling a temperature field of soil. A model is suggested for thermal and mass exchange processes in a layer in the influence area of the well including non-stationary heat conductivity [7, 11] and heat transfer with a filtration flow of underground water [13]. Unlike [9, 15], in this paper the problems of calculation modes of a heat-pumping device (HPD) for heat-supply and conditioning systems as well as determining initial and boundary conditions for chosen modes are addressed. For designing a calculation model the following modes (Fig.1) are chosen: a one-flow (only for heat supply or conditioning) and sign-changing (seasonal changes of load accompanied with changes of a flow direction due to switching of a heat pump from the heat supply to conditioning and back).

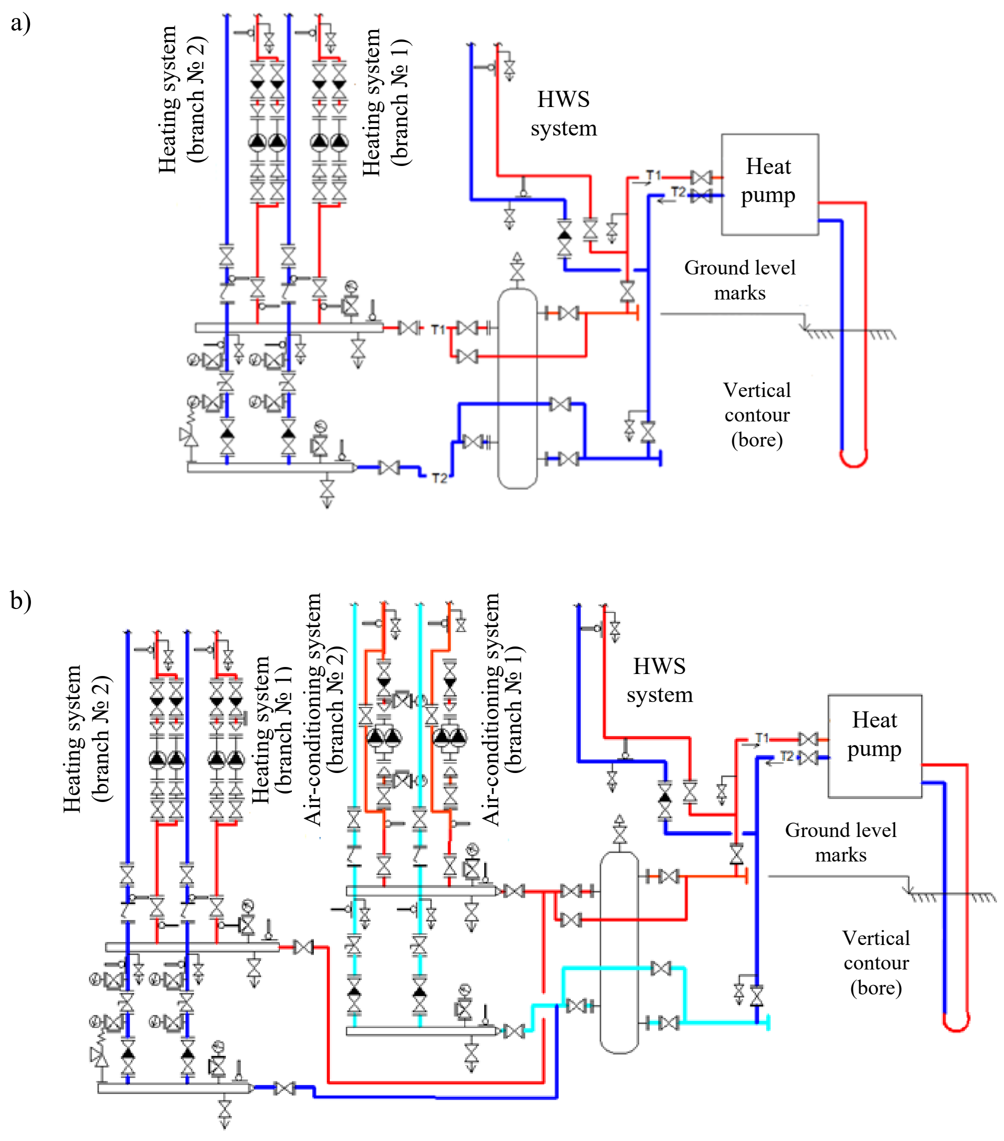


Fig. 1. Principal scheme:

a) heat supply; b) heat supply – conditioning

The operation of the well with filtration flows of underground water has been given particular consideration [12]. The Earth and the well have their own distinct features that need to be considered in a mathematical model. Firstly, a geothermal well is defined as a local source or sink of heat and basically it causes a local disruption of the global temperature field of the Earth (in case of heat supply) or a temperature drop (in case of heat removal) in the influence area of the well. After a heat pump stops, there is a gradual return to a background value. Secondly, a significant mass of soil massif and thermal resistance of a layer cause a considerable reduction in the influence area of the well decreasing the cooling or heating rate. In combination with small densities of background heat flows of a layer it is advisable to make use of a heat accumulator as well that operates more efficiently in a sign-changing operation mode of a heat pump implanting heat regeneration. Thirdly, non-stationary operation mode of the well is due to the operation of heat pump as part of systems of heat supply or heat supply-conditioning where demand for heat depends on a variety of factors stemming from technology, hydrogeology or climate. Fourthly, a filtration flow of underground water might have an influence on the operation of the well.

Mathematical modeling of a temperature field of a soil when geothermal energy is reduced to solving the problem of non-stationary thermal conductivity as in [17, 18, 20]. But in this case in order to design a model a cylindrical coordinate system that considers a background heat flow of the Earth to its surface was chosen (Fig. 2).

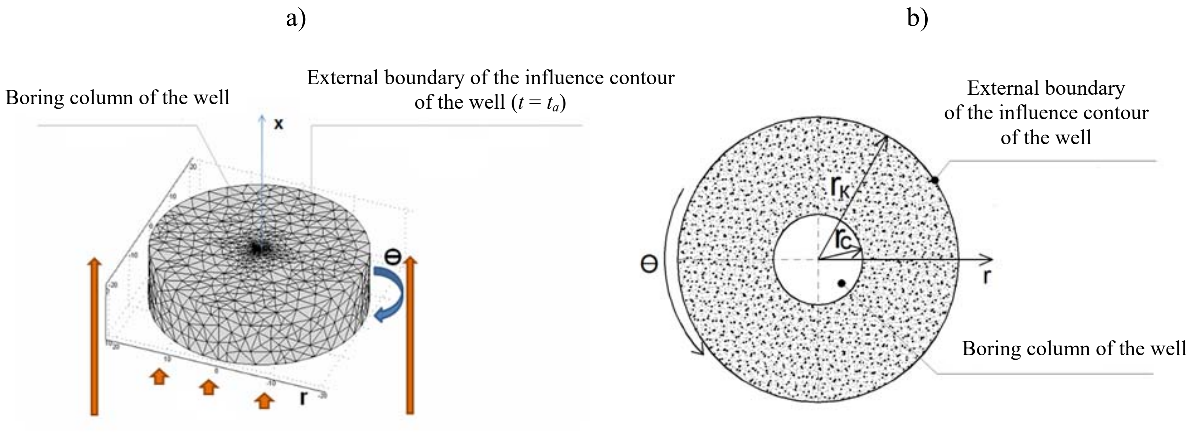


Fig. 2. Model of an operated soil massif:

a) general view; b) top view;

$r_к$ is the radius of a boring column, m; r_c is the radius of the well, m;

$Q_{фон}$ is the background flow of the Earth, Watt/m^2

A feature of the problem is non-stationary heat exchange that is caused by multiple alternating cycles of switching on a system of heat supply – conditioning with seasonal reverses of heat flow and switching it off [14].

$$\frac{\partial t}{\partial \tau} = a\left(\frac{\partial^2 t}{\partial x^2} + \frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\cdot\frac{\partial t}{\partial r}\right) + \frac{q_v}{c}, \tag{1}$$

where t is the temperature of a soil, ^{0}C; τ is the time время, sec; a is the coefficient of temperature conductivity, m^2/sec; r is a radial coordinate, m; q_v are sources and sinks of heat influenced by heat flows of the Earth and heat emissions through the surface, Watt/m^3; c is the heat capacity, J/(m^3·°C).

2. Boundary conditions for designing a model. The boundary conditions at the outlet of the well $T_{оси}$ were accepted depending on the technological modes.

1. Operating conditions without changing the direction of a heat flow:

— at the boundary of the influence area of the well in the layer the first-order boundary conditions with a constant background temperature of a soil $t(\infty, \tau) = t_{фон}$ are accepted;

— the second-order boundary conditions are specified on the surface of the boring column while the heat pump is operating:

$$-\lambda\frac{\partial t(r_c, \tau)}{\partial r} = q_{скв},$$

while it is not operating:

$$\frac{\partial t(r_c, \tau)}{\partial r} = 0,$$

where $q_{скв}$ is the density of a heat flow on the surface of the boring column of the well determined with a heat load of the system of heat supply and conditioning;

— there is a simplification that involves the second-order boundary conditions at the lower generating line of a design cylinder, background heat flow of the Earth is considered constant:

$$-\lambda\frac{\partial t(r, \tau)}{\partial r} = q;$$

— on the surface of the Earth the third-order boundary conditions determined with climatic conditions and heat emission with a relatively small error can be replaced by the first-order boundary conditions: $t(r, \tau) = t_{climate}$. The assumption is made due to a considerably larger coefficient of heat emission on the surface compared to the coefficient of heat emission of the soil from the surface before the heat exchange part of the well.

2. The operating conditions of the heat supply/air conditioning system in the sign-changing mode differ in the reverse of the heat flow on the surface of the boring column:

$$-\lambda \frac{\partial t(r_c, \tau)}{\partial r} = \pm q_{скв}.$$

For a qualitative description of the ratio of the supplied and deflected amount of heat for a sign-changing technological mode the concept of the coefficient of heat regeneration k_p is introduced that is given by the ratio of absolute values of the supplied and deflected heat:

$$k_p = Q_{подвод} / Q_{отвод}, \qquad (2)$$

where $Q_{подвод}$ is the amount of the supplied flow in the cold season, J; $Q_{отвод}$ is the amount of the deflected flow in the warm season, J.

3. Results of the numerical experiments and natural studies. Unlike [16], the investigated numerical model is based on discrete representation of an energy equation, boundary and initial conditions but for different densities of a heat flow and it is implemented using the *MathLab* software package. Change in the temperature field for cyclic heat deflection into the well of 100 Watt/m^2 is depicted in Fig. 3—4. The temperature of the soil layer of the well during one-flow mode from when the heat pump is first switched on increases rapidly and during the third year of the operation it becomes stable (Fig. 3a). During downtime (Fig. 3b) the temperature of the layer became equal and at the outlet of the well $T_{оси}$ a deviation from the background temperature remained in the range of 2 °C.

a) b)

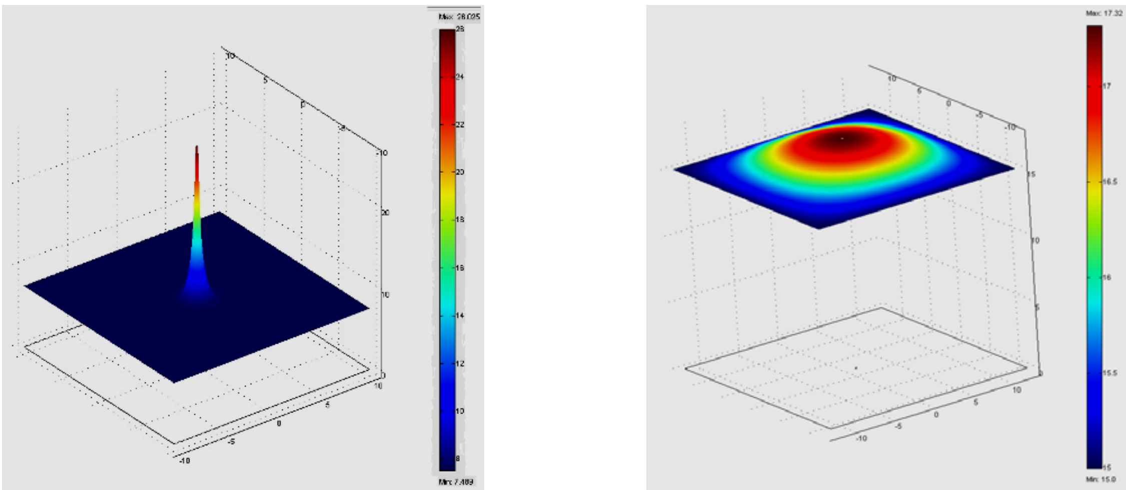


Fig. 3. Change in the temperature field:
a) active load during 6 months; b) downtime mode of the heat pump

c)

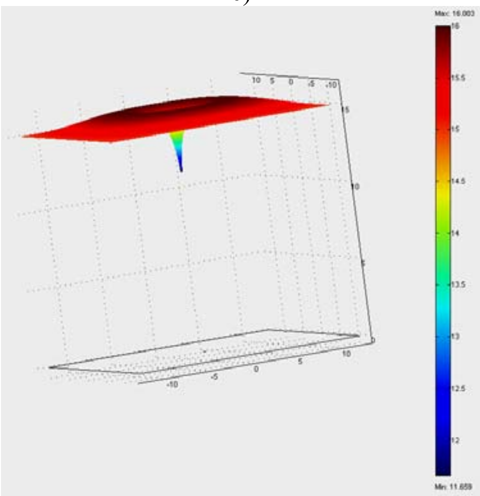
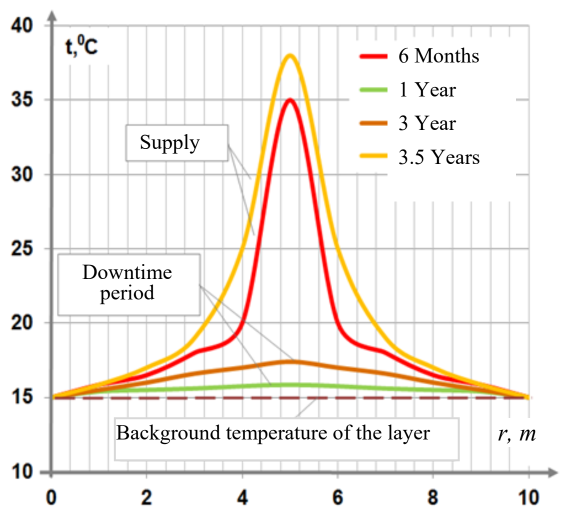
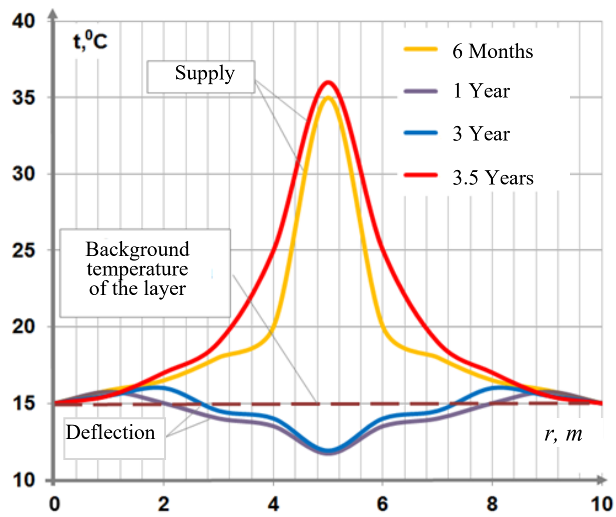


Fig. 3 (ending). Change in the temperature field:
c) during the sign-changing mode in the first-year stage

a)



b)



c)

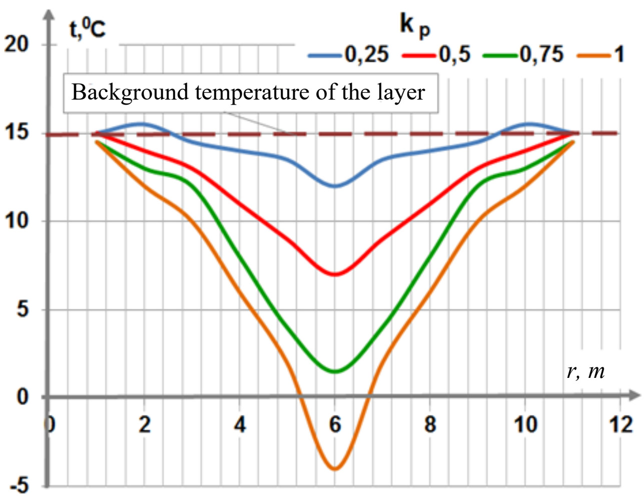


Fig. 4. Change in the temperature of the layer after the first switching until the quasi-stationary state is reached:
a) one-flow mode;
b) sign-changing mode;
c) temperature graph of the layer at k_p from 0 to 1

A quasi-stationary state that corresponds with a cyclic mode with no further increase in the temperature is reached at the stage after 2.5 years and during the downtime mode after 3 years (Fig. 4a). Compared to [1] changes in the temperature field when there is a reverse of the heat load on the layer (Fig. 4a, b) shows that during regeneration the quasi-stationary state is reached after 1.5 years.

4. Obtaining criteria dependencies. For possible distribution of the obtained results and their further use as generalizing dependencies the similarity theory was employed. The known criteria of similarity and criteria equations [19, 21] are not completely representative of the investigated phenomena. Therefore the following dimensionless complexes were used: the dimensionless active sink Q, dimensionless temperature θ. The temperature field is described with the dimensionless function with three dimensionless influencing parameters: $f = [Fo, \Theta, Q]$. The task involves the identification of the single-valuedness condition. Therefore the structure of the equations should be changed and the generalizing criteria of similarity modified in particular:

— the criterion Fo:

$$Fo = \frac{a \cdot \tau}{r_C^2}, \tag{3}$$

where a is the coefficient of thermal conductivity, m²/sec; τ is a typical time of change in the external conditions, sec; r_c is a typical size of a body (the radius of a well), m;

— active dimensionless heat flow:

$$Q = \frac{q_{нагр}}{q_{земли}}, \tag{4}$$

where $q_{нагр}$ is a specific reduced per an area unit of the boring column heat load on the well in a certain operating period, Watt/m^2; $q_{земли}$ is the background heat flow of the Earth, Watt/m^2;

— the dimensionless temperature:

$$\Theta = \frac{t_{остаточное}^{грунт} - \overline{t}_{ос}}{t_{фоновое}^{грунт} - \overline{t}_{ос}}, \tag{5}$$

where $t_{остаточное}^{грунт}$ is the temperature of the soil in the investigated period,^{0}C; $\overline{t}_{ос}$ is the average temperature of the environment of the investigated period,^{0}C; $t_{фоновое}^{грунт}$ is the background value of the temperature of the soil, ^{0}C.

The results of the calculation of the temperature at the bottom of the geothermal well $T_{оси}$ as a function of the determining parameters in a dimensionless size are presented in Fig. 5.

As a result of processing the obtained results in a dimensionless shape the following generalizing criteria equations are obtained:

— one-flow:

$$\theta = -5 \cdot 10^{-9} \cdot Q \cdot Fo^2 + 2 \cdot 10^{-8} Fo \cdot Q + 0.0003 \cdot Q + 5.1\,; \qquad (6)$$

— sign-changing:

$$\theta = -5 \cdot 10^{-9} \cdot Q \cdot Fo^2 + 2 \cdot 10^{-8} Fo \cdot Q + 0.0003 \cdot Q + 5.1(0.0002 \cdot k_p + 1.98)\,. \qquad (7)$$

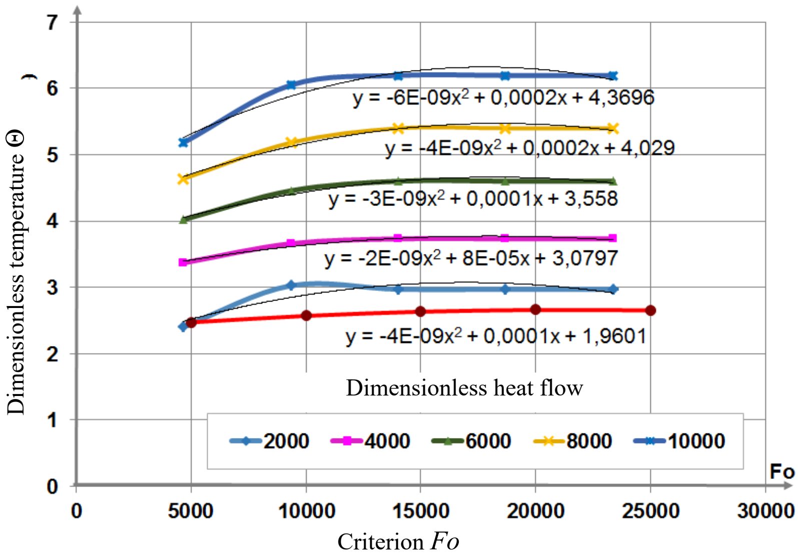


Fig. 5. Dependence of the dimensionless temperature Θ on the criterion *Fo* at the values of the dimensionless active (heat) flow *Q*

5. Comparison of the calculation results with the current setup. The model was checked by comparing the calculation values with the results of the measurements of the parameters of the current complex setup NIBE F 1145-12 operating at a dairy processing enterprise in Astrakhan region (Fig. 6).

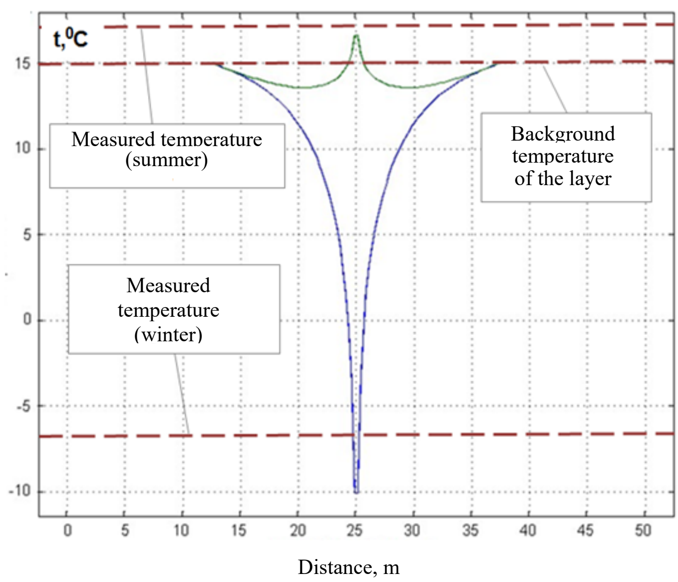


Fig. 6. Comparison of the results of calculations with the current setup

The data on the temperature distribution in the layer presented in the graph were obtained using a calculation method. The dotted lines correspond with the measure temperatures at the bottom of the well. The tops of the curved lines are the measured temperatures at the bottom of the well. The comparison of the calculation results and measurements show that in the summer season at the time the values were being recorded, the results were about 17 ^{0}C, the measured one was 18 ^{0}C. In winter the calculation one was −10 ^{0}C, and in fact −7 ^{0}C. The deviations in the measured and calculation values during the operation of the setup in the heat-saving mode were 1—2 ^{0}C, in the air conditioning mode — 3 ^{0}C. Based on the results, we conclude that the results obtained in the natural experiments are in good agreement with those of numerical modeling.

6. Methods of calculating changes in the temperature of the soil massif. The method of designing the heat supply and air conditioning systems is suggested considering long-term operation of the geothermal well and the technical and economic conditions of the major construction and technological solutions are analyzed. The order of the calculations of the method is presented in Fig. 7.

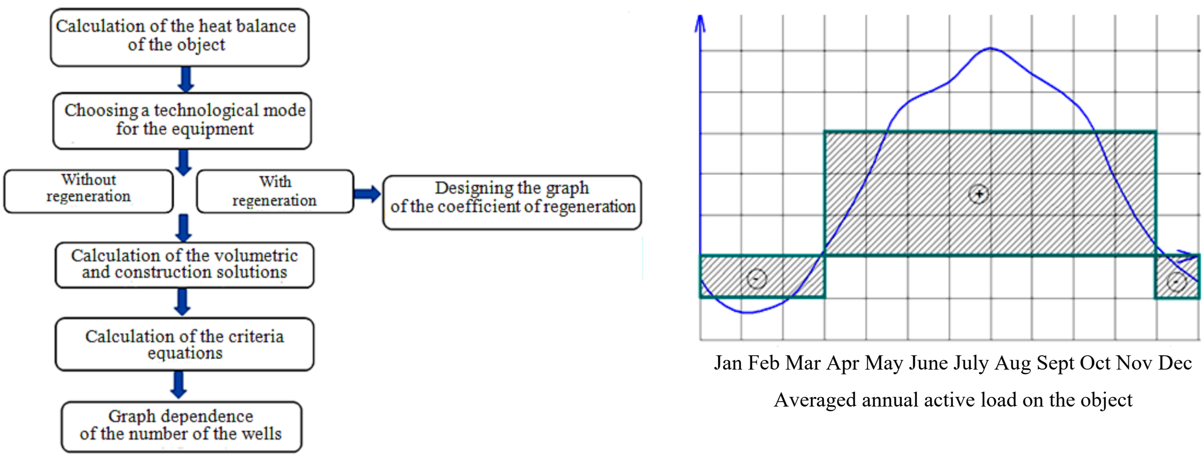


Fig. 7. Order of the calculations

The graphs of the data for calculating the number of the wells considering the natural and climatic conditions of the design area and the results of the studies of the soils are designed (Fig. 8).

The calculation method allows the energy-efficient calculation to be identified at the designing stage and a long-term operation of the heat pump to be predicted over time. The designing task can be depicted as a block scheme (Fig. 9).

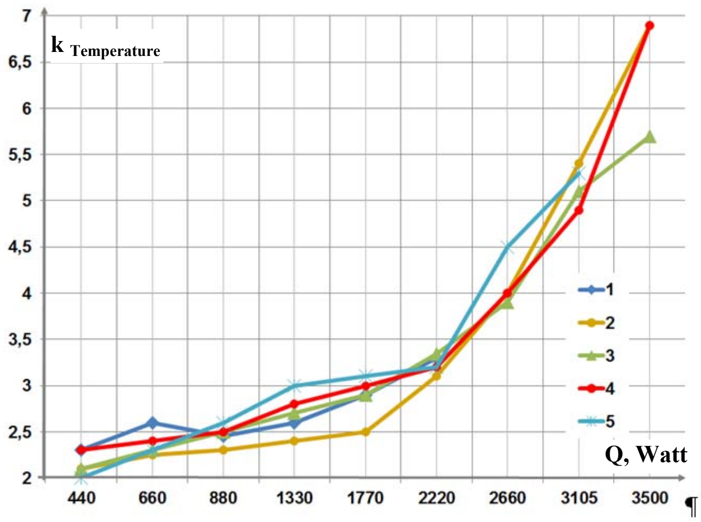


Fig. 8. Dependence of the number of the wells on the consumed energy of the heat pump with the transformation coefficient of no less than 2

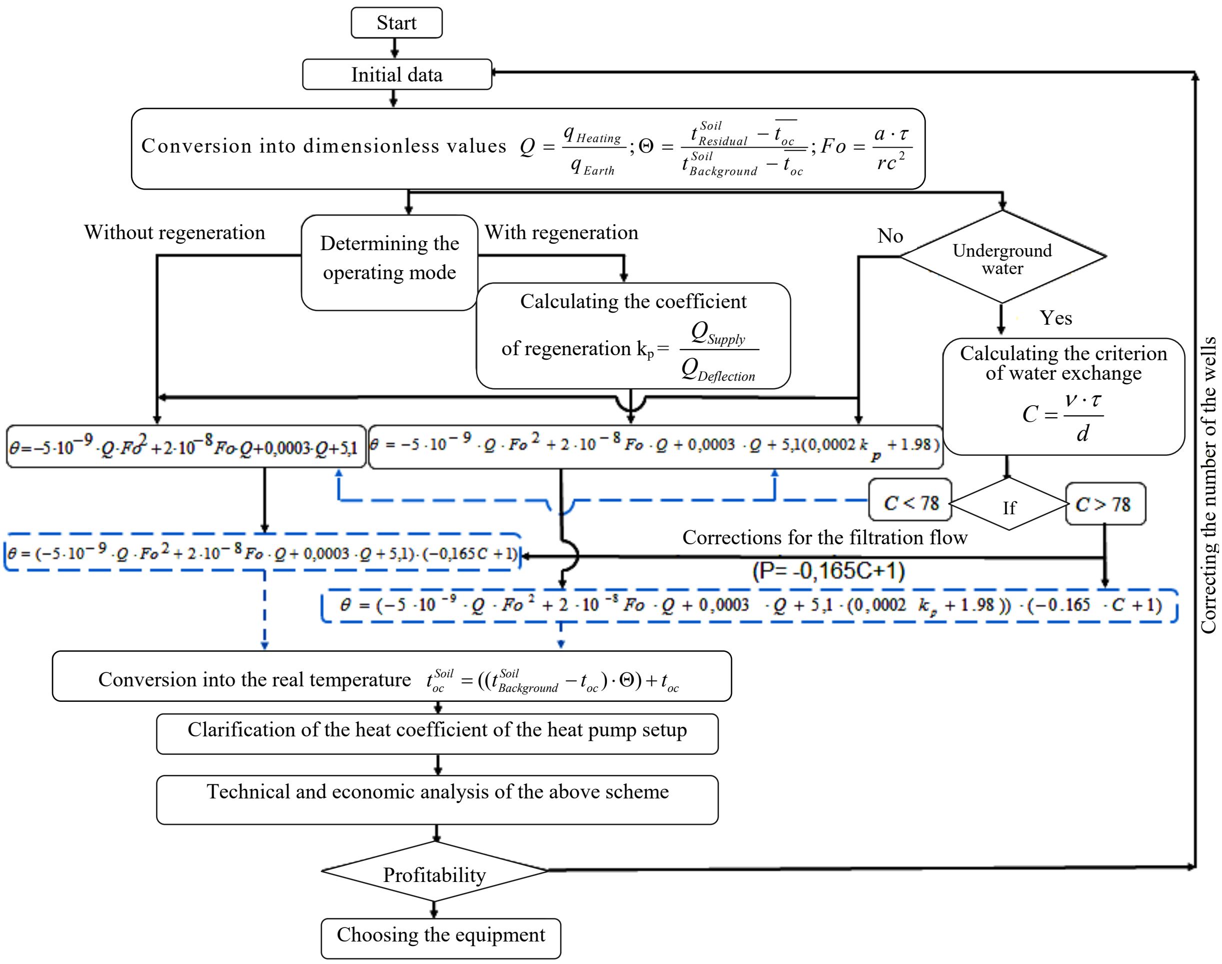


Fig. 9. Block scheme of the technical and economic parameters of the optimization of the composite systems of heat supply and air conditioning using a low-potential geothermal energy

Conclusions

1. A reduction in the temperature pump in the part of the layer adjacent to the bottom of the well used as a non-traditional source of heat in heat supply and air conditioning systems caused by non-stationary heat loads determined by climate conditions.

The temperature of the soil layer of the well during the one-flow mode after the heat pump is switched on increases and in the third year of operation it stabilizes. In the downtime period a reduction in the temperature is compensated for by the background heat flow and strives for the background temperature but increases by an average of 2—3 ^{0}C. In the following year of the operation the temperature increases and remains stable throughout the entire period. A switch to a quasi-stationary state is due to the fact that the operating well is only a source of excitation in the background temperature field of the Earth. During supply the heat flow gives the heat to the well. Following a break the heat pump restarts with the parameters of the previous stage, i.e. with an increased temperature of the layer, which has a positive effect on the operation of the thermal energy setup. During the sign-changing mode it is obvious that as the heat is deflected, the layer cools down and it heats up during supply but sequential reversing of the heat pump causes a system of thermal waves that lead to changes in the temperature of the well and have an effect on the technical and economic parameters of the equipment.

The results of the study enabled us to conclude that an annual drop in the temperature of the soil gradually reduces during regeneration. Regeneration allows the heat load to be compensated for. The volume of the soil massif that experiences changes of the temperature mode annually expands. The positive aspect is that in the mode with regeneration stabilization happens earlier than in the one-flow mode.

2. The obtained results of the study of heat-exchange between a heat carrier and soil in a geothermal well considering its long-term operation, heat supply and air conditioning systems in cyclic modes and the criteria dependencies for calculating the temperature ranges allowing for climatic cycles of heat loads were obtained.

3. The method of designing systems of heat supply and air conditioning employing a non-traditional heat source using geothermal wells was developed. The method allows for a long-term operation of wells in the seasonal cyclic mode of systems of heat supply and air conditioning with changes in the temperature ranges identified as a result of studies that determine a dynamic change in the coefficient of the transformation of heat of the current heat pumps.

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