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The toolkit of numerical modelling of the operating modes of the geothermal heat pump for heating and cooling with the account of climate conditions

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This article is devoted to the methods for increasing the efficiency of the heat pump heating and cooling system using the effect based on the energy saving principles. The major goal of study is the analysis of methods for increasing the efficiency of the geo-thermal heat pump for heating and cooling with the account of climate conditions. The paper considers the toolkit of numerical modelling of operating modes of the geothermal heat pump for heating and cooling (air conditioning) using geothermal water from the well, to determine the conditions that affect the temperature field around the well, taking into account the reversible direction of the coolant and climate conditions. The purpose of proposed toolkit is to obtain criteria equations for numerical modelling the operating parameters of the geothermal well, which is necessary for long-term operation of the system in the cyclic mode. Practical implementation of the numerical modelling technique allows achieving high spatial and temporal resolution, as well as taking into account the technical details of the combined system and forming the temperature of the soil mass around the well with the account of climatic conditions. The novelty of our toolkit for numerical modelling is the usage of the parametric approach for chosen to analyse different reversible modes of operation of the geothermal source heat pump for heating and cooling (air conditioning). This provides insights of effects during long-term operation of the geothermal heat pump without reaching negative temperatures at the well bottom, which can lead to the formation of ice, an increase the volume of the soil while freezing and the destruction of pipelines, respectively. The article examines the results of analyse of change the field of temperatures in the soil around the well for the long-term operation of the geothermal heat pump in two operation modes: stationary and reversible, during five years. Based on the obtained results, it was revealed that when the geothermal heat pump operates with a variable direction of the heat flow, the negative consequences of operation associated with the deviation of the temperature of the soil from the background value are reduced. The additional novelty aspect of numerical modelling is obtained for the operating parameters of a geothermal source heat with the account of long-term reversible operating modes of the geo-thermal heat pump. The toolkit of numerical modelling is well suited for the analysis of temperature in the bottom part of the well are revealed for heating and cooling due to the non-stationary thermal loads which determined from climatic conditions. The obtained results can be recommended as an innovative approach to optimization technical-economic indicators of geothermal wells during long-term operation of the geothermal heat pump in the reversible direction of the heat flow for heating and cooling purposes for improving the energy efficiency of system.

Keywords: *Numerical modelling; Geothermal heat pump; Geothermal well; Temperature field; Reversible operating modes; Heating; Cooling; Energy efficiency; Climatic conditions*

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1. Introduction

Widespread use of geothermal heat is hampered by low heat flow densities in most regions developed by man. The use of heat pumps to extract heat from geothermal wells helps to solve this problem, but experience in operating existing wells shows that the technical and economic indicators of wells deteriorate during operation. At the same time, reliable tools for taking these changes into account have not yet been developed [1-5].

In this regard, it is necessary to conduct studies aimed at solving the problem of long-term forecasting of changes in the parameters of the geothermal wells operating in heating and cooling modes, taking into account cyclic changes of the operating modes based on the energy saving principles [6].

The global requirement for sustainable energy provision and a political imperative for energy independence have combined to increase interest in the use of renewable energy sources to meet growing energy demands. Therefore, the heat pump (HP) systems introduces a new path for sustainable systems with clean energy supply and an improved energy efficiency. Current power systems are still dominated by fossil fuel-based electricity generation and operated on supply following the changing demand. Actually, the task of increasing energy efficiency should be realized by implementation of the innovation technologies of production and consumption of energy with the lowest energy losses.

The foreign investigations [7], lack of the numerical methods, which provides insights of effects during long-term operation of the geothermal heat pump without reaching negative temperatures at the well bottom, which can lead to the formation of ice, an increase the volume of the soil while freezing and the destruction of pipelines, respectively.

The features of influence the heat-circuit design solutions and operating modes of HP system on the value of the replacement factor of an alternative heating system haven’t been clarified till now. In the last decade, energy generation from HP system using RES has seen a sharp rise, but the energy supply from RES is inconstant because it is weather dependent. Thus, the energy production from installations using RES partially satisfies the energy demand. However, the power generation production exceeds the demand during certain time of a day during which has seen a high intensity of energy coming from variable renewable energy sources (VRES) [8]. This excess energy can be used through a power-to-heat technology. Reserves of traditional hydrocarbons such as gas, oil, coal are declining every year. And their use is associated with a negative impact on the environment. Today, there is a need to move to greater use of variable renewable energy sources, which are inexhaustible and can guarantee energy and environmental security. Among renewable energy sources, the use of low-potential environmental energy, converted to high-potential using heat pumps (HP), is promising. Experience shows that HP is one of the promising types of equipment for creating heat and cold supply systems.

At present, the problem of energy saving can be solved both by the thermal losses reduction and assimilation of the innovation technologies of generating, distribution, regulation and consumption of the heat [1]. The global requirement for sustainable energy provision and a political imperative for energy independence have combined to increase interest in the use of renewable energy sources to meet growing energy demands. Therefore, the heat pump systems (HPS) introduce a new path for sustainable systems with clean energy supply and an improved energy efficiency. Current power systems are still dominated by fossil fuel-based electricity generation and operated on supply following the changing demand. Actually, the task of increasing energy efficiency should be realized by implementation of the innovation technologies of production and consumption of energy with the lowest energy losses. The most efficient way of the energy saving is the introduction of heat pumps (HP) with tank accumulators, by virtue of their ability to utilize a renewable energy sources (RES) for heating systems [2]. Even so, the decisions presented in literature, which describe the peculiarities of tools for heat pump system with tank accumulator (TA) for permanent and intermittent heating modes of the public buildings are insufficient [3]. The foreign investigations [4], lack of the methods, which take into account HPS with TA and conditions of their practical application for permanent and intermittent heating modes of the public buildings at the environmental conditions. The features of influence the heat-circuit design solutions and operating modes of HPS on the value of the replacement factor of an alternative heating system haven’t been clarified till now. In the last decade, energy generation from HP using RES has seen a sharp rise, but the energy supply from RES is inconstant because it is weather dependent. Thus, the energy production from installations using RES partially satisfies the energy demand. However, the power generation production exceeds the demand during certain time of a day during which has seen a high intensity of energy coming from RES [5]. This excess energy can be used through a power-to-heat technology. Reserves of traditional hydrocarbons such as gas, oil, coal are declining every year. And their use is associated with a negative impact on the environment. Today, there is a need to move to greater use of renewable energy sources, which are inexhaustible and can guarantee energy and environmental security. Among renewable energy sources, the use of low-potential environmental energy, converted to high-potential using heat pumps (HP), is promising. Experience shows that HP is one of the promising types of equipment for creating heat and cold supply systems.

2. Analysis of the latest research of existing solutions enable to prevent freezing of the soil massive around the borehole during long-term operation of the geothermal heat pump systems

District heating capacities in the Ukraine are excessive, and their technologies are inefficient and outdated; capital stock is in a critical state, with most assets close to or beyond the end of their design lifespans. Energy losses are consider-able (hence much gas is wasted) and operating costs are high, largely due to inadequate maintenance [9,10].

Economic strategy of a sustainable development imposes certainly to promote efficiency and a rational energy use in buildings as the major energy consumer in Ukraine and countries of the European Union (EU). Buildings represent the biggest and most cost-effective potential for energy savings. Also, studies have shown that saving energy is the most cost-effective method to reduce green-house gas (GHG) emissions. The buildings sector is the largest user of energy and CO_2 emitter in the Ukraine and EU's. At present heat use is responsible for almost 80% of the energy demand in houses and utility buildings for space heating and hot water generation, whereas the energy demand for cooling is growing year after year. There are more than 150 million dwellings in Europe and more than 11 million housing units in the Ukraine [10]. Around 30% are built before 1940, around 45% between 1950 and 1980 and only 25% after 1980 [11-13]. Retrofitting is a means of rectifying existing building deficiencies by improving the standard and the thermal insulation of buildings and/or the replacement of old space conditioning systems by energy and environmentally efficient innovative heating and cooling systems [1, 2]. The European Parliament adopted the Renewable Energy Directive, establishing a common framework for the promotion of energy from VRES [14]. This directive opens up a major opportunity for further use of heat pumps for heating and cooling of new and existing buildings. Therefore, the EU countries must stimulate the transformation of existing building undergoing renovation into nearly zero-energy buildings besides improved energy efficiency using VRES in the near future. At present, the problem of energy saving can be solved both by assimilation of the innovation technologies of generating, distribution, and consumption of energy [14].

The most efficient technology of the energy saving is the implementation of the heat pumps, due to their possibility to use VRES for heating and cooling [10, 15-18].

Following the above described problem: despite the need for application and numerous researches in the field of thermal energy, the wide implementation of the geothermal heat pumps (GTHP) with the account of climate conditions, is hindered by the insufficient efficiency of existing solutions enable to prevent freezing of the soil during long-term operation of the geothermal heat pump systems (GTHPS) at the outside air temperature t_0 = – 8…26 °C, which is typical for the Ukraine and South-Eastern Europe [18].

However, the works presented in literature, which describe the peculiarities of work of the geothermal heat pump using VRES for the low-temperature heating are insufficient [18-19].

The foreign researches [20-25], lack the methods, which would describe the alternative geothermal heat pump unit and conditions of their practical application in the heating and air conditioning systems with different heat-exchange equipment for the environmental conditions of the Ukraine and the South-Eastern Europe. In [10, 23-25], the effect on the replacement rate by the design solutions and work modes of GTHPS is not considered. Therefore, the issue of conditions of the efficient of GTHP technologies needs the systematic approach.

The attention payed by the foreign works [24-25] is insufficient, concerning the justification of the choice of the scheme-construction solutions in the alternative system of the heat supply, taking into account the effect of the basic elements of the system and the modes of its operation on the GTHP replacing possibilities on the subsoil waters.

GTHP are efficient at transferring heat from a colder heat carrier to a hotter one through evaporation and condensation, using the heat of almost all environments. Heat pump units have proven their efficiency due to the fact that they transfer 3…5 times more energy to the consumer than they spend on its transmission. In addition, GTHP use environmentally friendly technologies with virtually no emissions of harmful substances into the environment [10, 26].

3. The aim and tasks of the study

The main aim of the study is to obtain criteria equations for numerical modelling the operating parameters of e geothermal well, which is necessary for operation of GTHPS in winter period in the cyclic mode. Practical implementation of the numerical modelling technique allows achieving high spatial and temporal resolution, as well as taking into account the technical details of the combined system and forming the temperature of the soil mass around the well with the account for the climatic conditions.

Our work differs from the known papers in the analyses of energy efficiency of the geothermal source heat pump systems for energy saving technologies using models, results of numerical simulation of processes in GTHPS and experimental studies for the Ukraine and the South-Eastern Europe, which allows to predict and prevent freezing of the soil around geothermal well. This makes it possible to perform a rational choice of the conditions for the efficient operation of the GTHPS in winter period. This reduces the consumption of the hydrocarbon fuel and ensures the substantial energy saving and ecological effects in addition to those economical.

To achieve the goal, it is necessary to solve the following tasks:

– to develop the toolkit of modelling is the usage of a parametric approach for chosen to analyse different reversible modes of operation of the geothermal source heat pump for heating and cooling (air conditioning);

– to establish conditions that prevent the negative consequences of ice formation around the well during long-term operation of the geothermal source heat pump, which can lead to the formation of ice, an increase the volume of the soil while freezing and the destruction of pipelines, respectively

4. Research methodology and data processing

The characteristics of the temperature field depends on the operating mode of the ground source heat pump are considered in works [10, 26]. The temperature field of the soil around the well for the long-term operation depends on operating modes. When GTHP works on stationary and reversible operation modes, the account of these changes in the numerical modelling technique allows to achieve high spatial and temporal resolution, as well as taking into account the technical details of the system, and to form the temperature of the soil around the well with the account for the climatic conditions [19, 26]. Field studies have proven that when installing GTHPS, in the first year there is a significant change in temperature are relative to the massive. The first three years the geothermal well characterized by slight continuous change in temperature and then the operation of the well characterized by steady massive temperature on the casing well, significantly different from the background massive temperature [25, 26]. In most cases, field measurements are not applicable due to the inaccessibility of the research object located at a considerable depth.

The soil massive has significant thermal inertia, smoothing out at least daily temperature fluctuations. These features made it possible to replace the actual load curve in the model with discrete sections that have a constant average thermal load over the design period (Fig. 1).

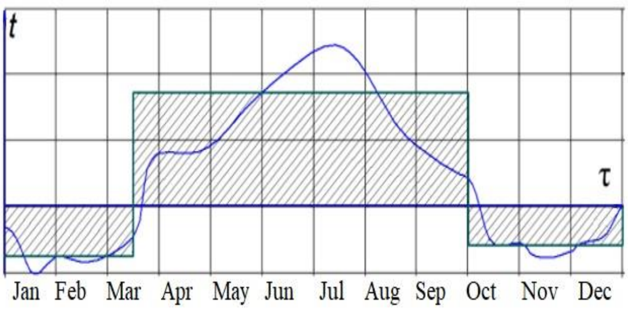


Figure 1 *– The averaged loads in the conditions of the problem being solved*

Under conditions of alternating operation (winter season for heating, summer season for cooling), the initial conditions for the first and second stages will be identical to expressions [25] adjusted for the direction of heat flow. Excellent initial conditions will be available starting from the third stage. The third stage is turning on the heat pump in reverse mode relative to the first stage. When the direction of the heat flow changes, heat is regenerated in the soil massive, i.e., if at the first stage heat is supplied, at the second stage heat is removed, then at the third stage it is supplied again. Thus, the third stage – turning on the heat pump after a break – is a complex temperature field resulting after cooling of the soil massive ($\tau_1 < \tau < \tau_2$), a heat flow with the opposite sign is superimposed, changing the temperature field.

The initial boundary conditions of operation the heat pump in heating mode conditions are:

$$t = t_0\left(r, \tau_2\right), \text{s}, \tag{1}$$

where τ_2 – the operating time of the heat pump installation of the third reverse mode period; t – soil temperature.

The soil temperature of the second reverse mode period:

$$t_1 = t\left(r, \tau\right), \text{°C}. \tag{2}$$

The soil temperature of the third reverse mode period:

$$t_3 = t\left(r_0, \tau\right), \text{°C}. \tag{3}$$

The boundary conditions of the first kind of expression are identically equal.

Boundary conditions of the second kind of expression, under conditions of alternating operating modes are:

$$\frac{\partial t}{\partial r}\left(r, \tau\right) = -\frac{q}{\lambda}. \tag{4}$$

Boundary conditions of the second kind are q_E – the heat of the Earth, i.e. the heat flow is assumed to be constant:

$$-\lambda \frac{\partial t}{\partial r}\left(r, \tau\right) + q\left(\tau\right) + q_E = 0. \tag{5}$$

where $q(\tau)$ – the heat flow through the Earth's surface into the environment, W/m^2.

As noted above, the unsteady operating mode of the heat pump, determined by climatic conditions and the technological history of production, leads to changes in the boundary conditions.

For description in the reversible mode of operation of the GTHP quantitatively, a regeneration coefficient k_p was used, which is defined by the ratio of the absolute values of the removed and supplied heat follows:

$$k_p = Q_{in} / Q_{out}, \tag{6}$$

where Q_{in} – the amount of supplied flow during the cold season, W/m^2; Q_{out} – the amount of diverted flow during the warm period of the year, W/m^2.

The range of changes in the regeneration coefficient is possible only in the ratio 0…1. Due to the difference in temperature and climatic characteristics of the regions and the operating characteristics of the heat pump, the values of the regeneration coefficient during processing must be taken modulo.

Due to the reversibility of the working process, the heat pump can operate effectively both in heating mode in cold season, and in cooling mode in hot season (room air conditioning).

In the most cases, secondary heat isn't used. It's disposed of into the atmosphere. From an economic point of view, it is more expedient to direct this heat back into the well, ensuring restoration of the temperature field in order to increase the thermodynamic efficiency of heat pumping equipment.

To build the temperature field for the reversible process must be taken into account the current regeneration coefficient k_r.

The normalized thermal characteristics of the GTHP operating in the reversible mode are shown in Fig. 2, a.

The calculation conditions determine the alternation of periods when the heat pump is turned on (Fig. 2, b) with periods of shutdown with a cyclicity determined by the time of year. The time to achieve a substitutionary regime is determined by calculation and is within five years, which is also confirmed by the operational parameters of existing wells. Limit states of the soil massive temperature are reached at the end of the cycle, i.e., for example, at the end of the heating season, and therefore the calculated values used to determine the operational characteristics were recorded at this point in time.

The alternation of heat removal modes (operation of the heat supply system in winter) and heat supply (operation of the air conditioning system in summer) corresponds to different temperature regimes of the soil massive.

It should be noted that the alternating mode of operation of the heat pump is accompanied by the regeneration of heat in the reservoir, and under ideal conditions, zero balance can be considered the best, when the amount of heat taken from the reservoir in winter is equal to the amount of heat supplied in summer. That is, even in adiabatic mode, the of soil massive temperature should not change in the long term. The alternation of periods of switching on the heat pump is determined.

In Fig. 2, b shows a diagram of the main stages of operation of a heat pump in an alternating mode (“+” – supply of load to the well, “-” – removal).

Modelling the processes of change in the thermal field of a soil under conditions of alternating non-stationary heat flow is an extremely complex task, since it requires a physical and mathematical description of a complex temperature field formed under the influence of various non-stationary mechanisms that determine the process of heat collection or heat removal, including external climatic conditions, heat pump parameters, changes in soil characteristics [25].

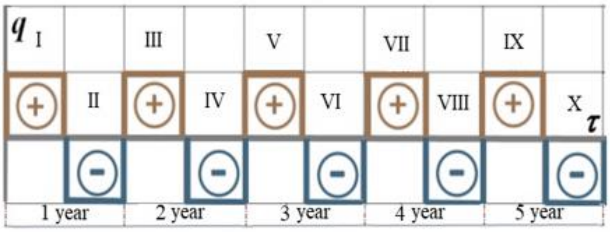


Figure 2 *– GTHP loads in alternating mode: main stages of heat pump operation: I – 6 months; II – 1 year; III – 1,5 years; IV – 2 years; V – 2,5 years; VI – 3 years; VII – 3,5 years; VIII – 4 years; IX – 4,5 years; X – 5 years*

The numerical model is based on a discrete representation of the energy equation, boundary and initial conditions, but at different heat flow densities, and is implemented using the MathLab software package. The graphs of temperature field during all year-round (Fig. 3-4) under alternating technological modes (at changes of active loads) characterizes the operation of the heat pump with regeneration.

Calculations are made in the range of active values from 100 to 25 W/m^2 with regeneration coefficient k_p = 0,25. The results of the first stage during six months of operation of the heat pump unit with alternating flow direction are shown in the Fig. 3.

At the second stage during first year, a different active load is introduced in the direction and the type of thermal wave differs greatly from the previous stage (Fig. 4), acquiring the distinct form of a thermal wave. The nature of the temperature distribution is also radial from the borehole axis, but it has a difference in the values of the soil temperatures. At a distance of 10…15 m from the borehole, traces of the thermal impact of the first cycle are preserved in the form of zones of elevated temperature (above background values), at a distance of 7…8 m from the borehole axis, the temperature decreases with a significant gradient.

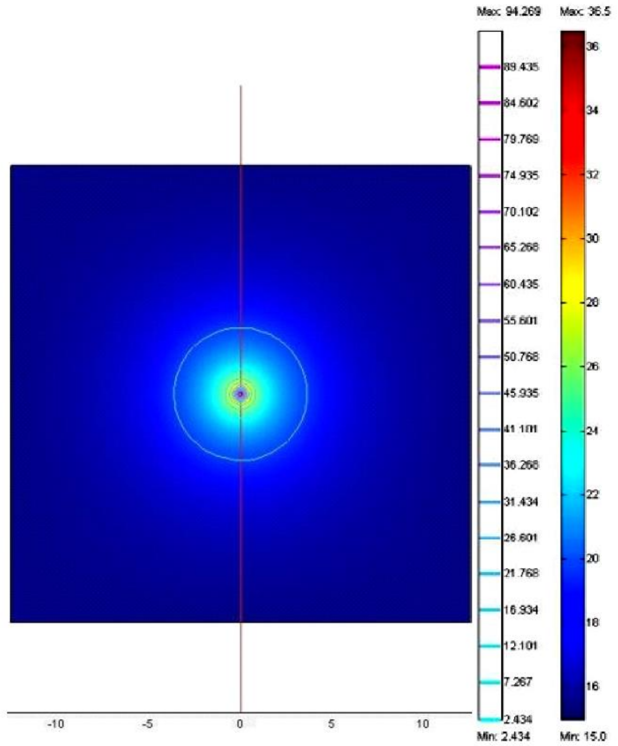


Figure 3 *– Temperature field with positive thermal load during six months of the year*

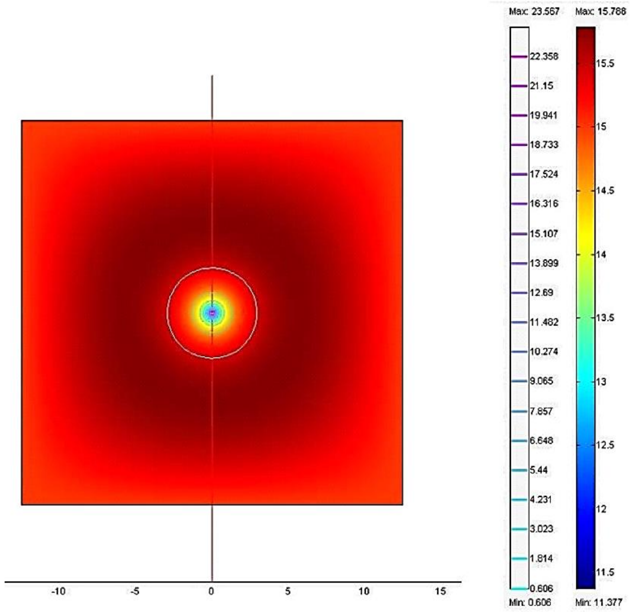


Figure 4 *– Temperature field with alternating load on the of the soil massive during first year*

Taking into account the subsequent stages of the heat pump operation in the alternating (discharge or supply) modes, the pattern of changes in the temperature field is as follows: given the predominance of heat supply (k_p = 0,25), the temperature at the bottom hole of the geothermal borehole T_0 predictably increases, compared to the first stage of operation (six months), the temperature increased by 1,5 °C.

The change in the formation temperature relative to the second stage during two years is insignificant and amounts to an average of 0,2 °C, which is within the calculation error.

Research has shown that with regeneration, the temperature change according to the cyclic law is achieved earlier than without regeneration. Thus, after 2,5 years, a quasi-stationary state occurs, when seasonal changes enter the established cyclic mode. Checking the calculation results as of three years confirms the conclusions made.

Summarizing the results of the study, it can be stated that the operation of the heat pump in the alternating mode is more efficient than the operation mode with intermittent supply or removal of heat without its reversal. The decrease in the temperature head of the heat pump is determined by the approach of the temperature in the geothermal well to the background temperature value.

Results of influence on the temperature field at the stage of the first year of operation of the regeneration coefficient kp in the range of 0.25…1 for values of active loads in the range of +100…−100 W.

The change in the formation temperature from the values of the regeneration coefficient (k_p = 0; 0,25; 0,5; 0,75; 1) at different values of the thermal load is shown in Fig. 5.

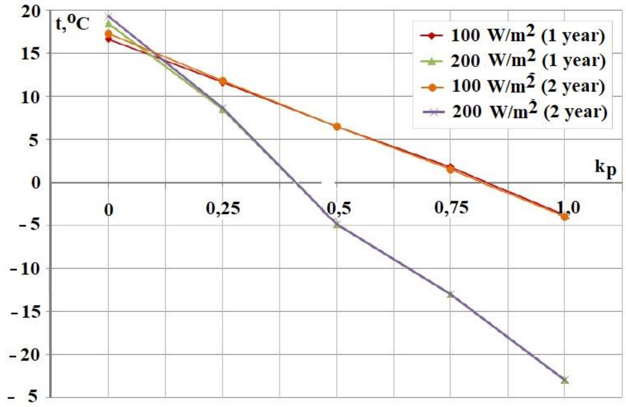


***Figure 5** – Dependence of soil temperature on the regeneration coefficient k_p*

Obviously, when heat is removed, the soil massive cools down. When heat is supplied the soil massive heats up. However, sequential reversal of the heat pump leads to the appearance of thermal waves in the system, which cause changes in the well temperature and affect the technical and economic parameters of the equipment. The results of simulation allowed us to conclude that the annual drop in ground temperature will gradually decrease under regeneration conditions. Thus, the regeneration process allows to compensate the missing values of the heat load. At the same time, the volume of the soil massive is annually affected by changes in temperature conditions, that will expand every year.

It should be noted that in the operating mode with regeneration, it is necessary to introduce a limitation on reaching negative temperatures at the bottom of the borehole To, which can lead to ice formation. Although it leads to some increase in heat removal due to an increase in thermal conductivity and the inclusion of a phase transition in the heat exchange process, this is a negative operational and technological factor.

It should be noted that this phenomenon leads to additional problems:

– an increase in the volume of soil formation during freezing leads to its swelling, which can negatively affect at further operation of the well;

– compression of the collector or probe pipelines occurs, up to their destruction. Based on the results obtained, it can be concluded that when a geothermal borehole operates with an alternating direction of heat flow (with regeneration), the long-term consequences of operation associated with the deviation of the formation temperature from the background value are reduced.

5. Results of simulation, conclusions and decisions

In order to be able to disseminate the results obtained and their further practical use in the form of a generalizing relationship, the theory of similarity was used. The known similarity criteria and criterion equations [26] do not fully reflect the studied phenomena, in connection with which the following dimensionless complexes were proposed: dimensionless active flow Q, dimensionless temperature θ. The temperature field of the reservoir is described by a dimensionless function with three dimensionless influencing parameters:

$$f = \left[Fo, \theta, Q \right]. \quad (7)$$

The complex nature of the mutual influence of the defining parameters does not allow to formalize a unique solution, and therefore a traditional approach is used to view the form of the criterion equation as a power dependence.

According to above described equations by the dimensionless criterion, the general equation is taken in the form [26]:

$$\theta = \sum c \cdot Fo^{n} \cdot Q^{m}, \tag{8}$$

where: $Fo = (\alpha \cdot \tau)/(r_w^2)$ – Fourier value; n – power index of the Fo value; α – thermal diffusivity coefficient, m²/s; τ – characteristic time of change of external conditions, s; r_w – characteristic size of the well (well radius), m; Q – active dimensionless heat flux; m – the power index of the dimensionless active heat flux; c – determined ratio.

The general equation (8) for the operating mode with a change in the direction of the heat flow (with regeneration) can be described as a power series.

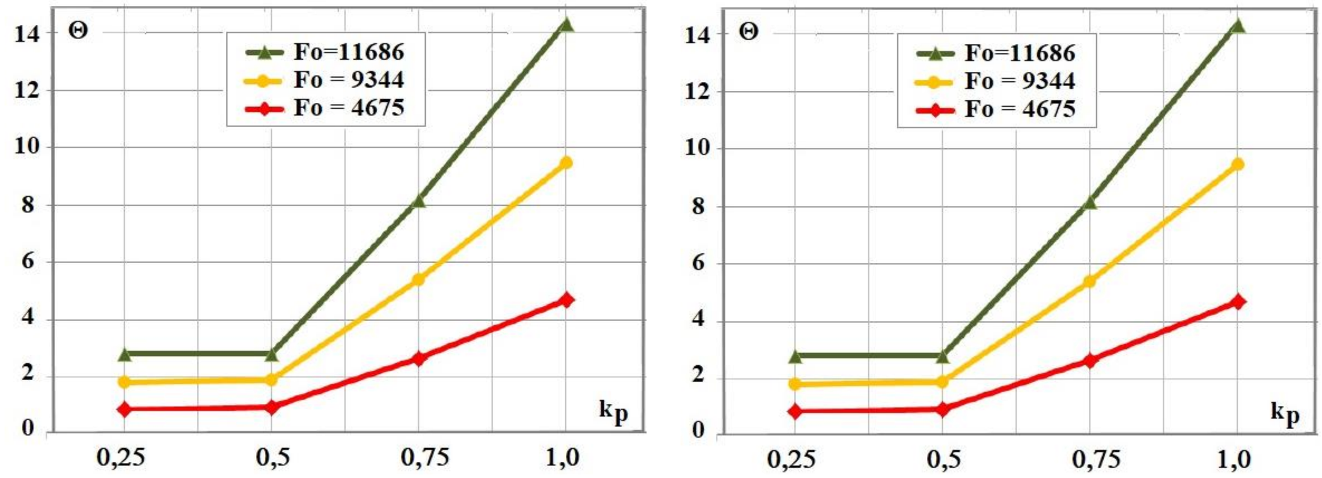
Under conditions when the heat pump operates in the mode of alternating active heat flow, the general laws of the process are preserved. The difference of this operating mode of the heat pump is the use of the heat regeneration effect due to the accumulative capacity of the soil. This feature determines the possibility of using general equation (6) as a basic one with its addition in the form of a correction for the regeneration coefficient kp.

Then the expression will look as [10]:

$$\theta = f\left(k_p\right) \cdot \left(k_1 \cdot Fo^2 \cdot Q^2 + k_2 \cdot Fo \cdot Q + \ldots + k_n \cdot Fo \cdot Q\right), \tag{9}$$

where: $f(k_p)$ – function taking into account the regeneration coefficient; $k_{1,2,\ldots n}$ – determined coefficients.

At switching the heat flow, the formation is supercooled or superheated, and this is according a smaller temperature difference for the refrigeration machine, and therefore, lower energy consumption. The dependence of the dimensionless temperature on the regeneration coefficient k_p is shown in the graph (Fig. 6). Numerical modelling was performed for Fo values from 4675 to 11686 and dimensionless active flow Q is 2000 and 4000.



a) *b)*

***Figure 6** – Dependence of dimensionless temperature θ on regeneration coefficient k_p and dimensionless active dimensionless heat flux Q in the range for different Fo values: a) Q = 2000; b) Q = 4000*

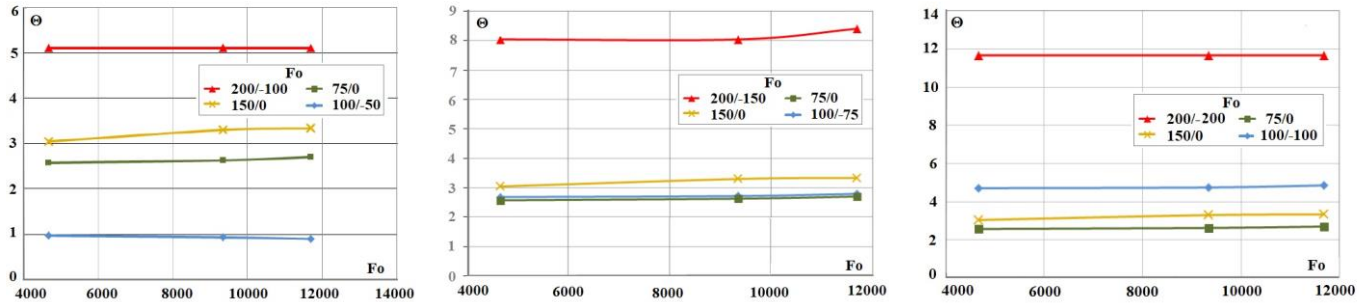
Taking dependence (8) as a basis, the analysis was performed by successive comparison of the obtained dimensionless temperature at different values of the regeneration coefficient with the available results for the operation of the heat pump without regeneration [10].

Graphs (Fig. 6) shows the effect of regeneration on the values of the dimensionless temperature at regeneration coefficients k_p from 0,5 to 1 in the range of active loads on the borehole. The presented values are calculated by the module in the range Fo from 4675 to 11686. The upper and lower lines (Fig. 6, a) are the results with regeneration. Middle lines are without regeneration. At k_p = 0,5, the values of the dimensionless temperatures θ are as follows: the difference between 100/(-50) and 75/0 is approximately 1,5; at 50/0 and 200/(-100) is about 2.

As can be seen from the results presented (Figure 7, a), regeneration leads to an increase in the heat transformation coefficient in the heat pump. Let us consider three work plans: 200/100, 200/150 and 200/200. Heat regeneration leads to an increase in the dimensionless temperature, i.e. the work during the next switching of "heat – cold" and "cold – heat" begins not with the background temperature of the soil, but with a more favorable temperature for the heat pump unit. For example, heat extraction for the purposes of heat supply begins with a higher soil temperature than the background reservoir temperature. As calculations have shown, for a long time (in this case, the range is more than 30 days) during reversal, the heat pump operates at a lower temperature head.

The results of data processing at k_p = 0,75 and active loads (75/0, 100/-75, 150/0, 200/-150) are presented on Fig. 7, b. Two upper lines are the results of data processing with regeneration 200/-150 and without regeneration 150/0, respectively. The difference between them is at an average value of θ = 5. Two lower lines are the results of data processing with regeneration 100/-75 and without it 75/0, respectively. The difference in the value of the dimensionless temperature is very small and is on average 0,3.

The results of data processing at k_p = 1 and active loads 75/0, 100/−100, 150/0, 200/-200) are presented on Fig. 7, c. Top line is 200/-200 (with regeneration) and second from the bottom is 150/0 (without regeneration) – the difference is θ = 8. The second from the top is 100/-100 and the bottom is 75/0, The difference in the value of the dimensionless temperature θ = 2.



a) *b)* *c)*

Figure 7 *– Regeneration of temperature field at: a)* k_p*= 0,5; b)* k_p*= 0,75; c)* k_p*=1*

Results of digitized calculation data are shown on Fig. 8.

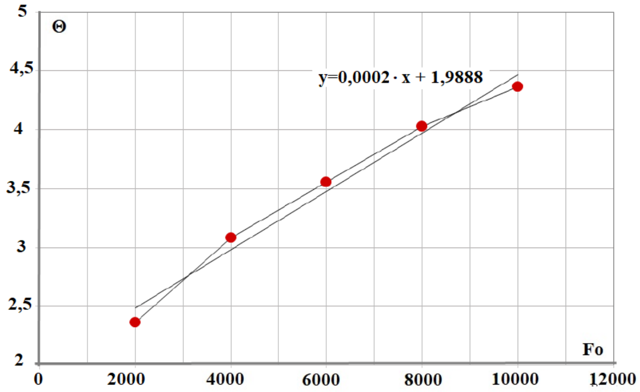


Figure 8 *– Dependence of values of dimensionless temperature of temperature field without regeneration*

Based on this, the following form of the refined criteria equation (8) was obtained with a correction for the regeneration coefficient k_p. Thus, the obtained equation (trend line) can serve as a correction to the calculation of the main expression (8). Then the equation for the alternating heat flow of a geothermal well with a correction for the regeneration coefficient k_p will look like:

$$\theta = -5\cdot 10^{-9}\cdot Fo^2\cdot Q + 2\cdot 10^{-8}\cdot Fo\cdot Q + 3\cdot 10^{-4}\cdot Q + \\ +5{,}1\left(2\cdot 10^{-4}\cdot k_p + 1{,}98\right) \qquad (10)$$

Depending on the operating mode of the heat pump, different temperatures of the reservoir are established in the long term (Fig. 9). If you simply remove heat from the reservoir, the temperature drops and after a couple of years is established at some lower level; if you alternate supply and discharge, then it begins to approach the background; if the regeneration coefficient is equal to 1, then it is practically background.

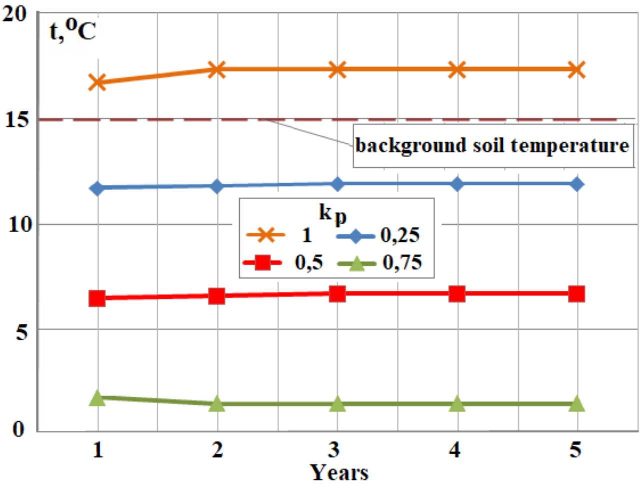


Figure 9 *– Comparative characteristics of operating modes depending on the regeneration coefficient* k_p *during operation of the heat pump*

Data graphs for calculating the number of wells (*n*) has been generated [10], taking into account the natural and climatic conditions of the design area and type of the soil (Figure 10). Thus, the toolkit of numerical modelling of the operating modes of the geothermal heat pump for heating and cooling allows to predict the energy-efficiency of the heat pump during the long-term operation in a cyclic mode with the account of climate conditions.

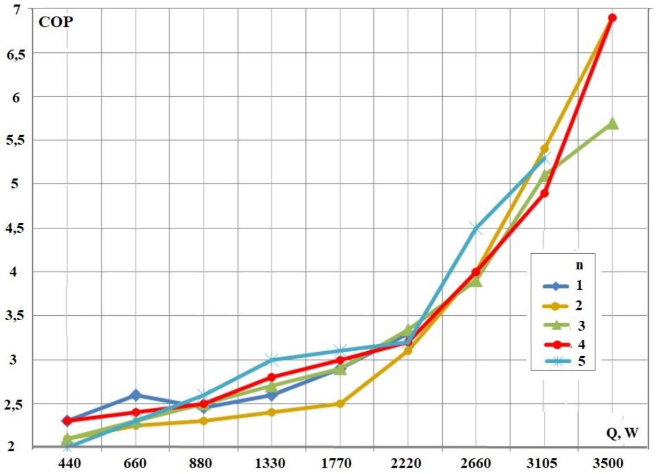


***Figure 10** – Dependence of number of wells on the energy consumed by the heat pump with a heat transformation coefficient COP > 2 [10]*

6. Conclusions

The obtained results confirmed that under the operating conditions of a heat pump with an alternating heat flow (with regeneration), the soil temperature field stabilizes already in the second year of operation. The achievement of a quasistationary state in each of the modes is explained by the fact that an operating geothermal well is a local source (sink) of heat in the background temperature field of the Earth. When heat is supplied, the well's heat flow gives off to the Earth's surface, and when removed, the decrease in temperature is compensated by the background heat flow. The radius of influence of the well is determined by its operating parameters, the thermophysical properties of the soil and the density of the background flow. If we talk about the heat supply mode, then in the case of heating, heat is taken from the ground and the reservoir temperature drops, the temperature approaches the background. When we continuously take away heat, the deviation from the background is greater. The heat exchange processes between the operation of heat supply and air conditioning systems in cyclic modes are summarized and criterion dependencies are obtained for calculating temperature heads, taking into account the climatic cyclicity of heat loads.

The, criterion dependencies were obtained for calculating the operating parameters of a geothermal well, taking into account its long-term operation in a cyclic mode.

A methodology for designing heat supply and air conditioning systems using geothermal wells is developed.

The toolkit for designing heat supply and air conditioning systems using geothermal wells is developed. This toolkit takes into account the long-term operation of wells in the seasonal cyclic mode of operation of heat supply and air conditioning systems with the change in temperature pressures revealed as a result of the study.

The toolkit allows to determine the dynamic change in the heat transformation coefficient of the geothermal heat for different operating modes: for heating and cooling with the account of climate conditions.

The toolkit of numerical modelling using the parametric approach for different reversible modes of operation of the geothermal source heat pump for heating and cooling (air conditioning) provides insights of effects during long-term operation of the geothermal heat pump without reaching negative temperatures at the well bottom. Thus, the toolkit prevents formation of ice, an increase the volume of the soil while freezing and the destruction of pipelines, respectively.

CRediT author statement

Alla Denysova: development of the toolkit, project administration, supervision. **Pavlo Ivanov**: numerical modelling and analysis of results of simulation

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Інструментарій для чисельного моделювання режимів роботи геотермального теплового насоса для опалення та охолодження з урахуванням кліматичних умов

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Стаття присвячена методам підвищення ефективності системи опалення та охолодження з використанням ефекту, заснованого на принципах енергозбереження. Основною метою дослідження є аналіз методів підвищення ефективності геотермального теплового насоса для опалення та охолодження з урахуванням кліматичних умов. У статті розглядається інструментарій чисельного моделювання режимів роботи геотермального теплового насоса для опалення та охолодження (кондиціонування повітря) з використанням геотермальної води зі свердловини, для визначення умов, що впливають на температурне поле навколо свердловини, з урахуванням зворотного напрямку теплоносія та кліматичних умов. Метою запропонованого інструментарію є отримання критеріальних рівнянь для чисельного моделювання робочих параметрів геотермальної свердловини, що необхідно для тривалої роботи системи в циклічному режимі. Практична реалізація методики чисельного моделювання дозволяє досягти високої просторової та часової роздільної здатності, а також врахувати технічні деталі комбінованої системи та сформувати температуру ґрунтового масиву навколо свердловини з урахуванням кліматичних умов. Значимістю нашого інструментарію чисельного моделювання є використання параметричного підходу для аналізу різних оборотних режимів роботи геотермального теплового насоса для опалення та охолодження (кондиціонування повітря). Це дозволяє зрозуміти наслідки тривалої роботи геотермального теплового насоса без досягнення негативних температур в нижній частині свердловини, що може призвести до утворення льоду, збільшення об'єму ґрунту при замерзанні та руйнування трубопроводів, відповідно. У статті розглядаються результати аналізу зміни поля температур у ґрунтовому масиві навколо свердловини протягом тривалої роботи геотермального теплового насоса у двох режимах роботи: стаціонарному та зворотному. На основі отриманих результатів чисельного моделювання виявлено, що при роботі геотермального теплового насоса зі змінним напрямком теплового потоку негативні наслідки роботи, пов'язані з відхиленням температури ґрунту від фонового значення, зменшуються. Додатковою новизною чисельного моделювання є врахування робочих параметрів геотермального теплового насоса з урахуванням тривалих реверсивних режимів роботи геотермального теплового насоса. Запропонований інструментарій чисельного моделювання добре підходить для аналізу температури в нижній частині свердловини, виявленої для нагрівання та охолодження, через нестаціонарні теплові навантаження, що визначаються кліматичними умовами. Отримані результати можна рекомендувати як інноваційний підхід до оптимізації техніко-економічних показників геотермальних свердловин протягом довготривалої експлуатації геотермального теплового насоса з реверсивним напрямком теплового потоку для цілей нагрівання та охолодження для підвищення енергоефективності системи.

Ключові слова: *Чисельне моделювання; Геотермальний тепловий насос; Геотермальна свердловина; Температурне поле; Реверсивні режими роботи; Опалення; Охолодження; Енергоефективність; Кліматичні умови*

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