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Modeling of the temperature field in the soil massive for different operating modes of the ground source heat pump

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ABSTRACT

The paper considers modeling the influence of the operating modes of the ground source heat pump for heating and air conditioning systems using geothermal source of energy from borehole on the temperature of the soil formation around the borehole with the account of climate conditions of Ukraine. The proposed methodology of modelling of the ground source heat pump with the account of reversible direction of heat flow for heating and cooling work modes contributes to the field of energy system models. The ultimate goals are to obtain criterion dependencies for calculating the operating parameters of a geothermal borehole and to develop a methodology for designing geothermal boreholes taking into account their long-term operation in a cyclic mode. The idea behind the method allows high spatial and temporal resolution as well as the inclusion of the technical details of the power system and formation the temperature of the soil massive around the borehole for the climate conditions of the Ukraine and South-East Regions of Europe. The novelty of this method is the usage of a parametric approach is chosen to analyze different reversible operating modes of the ground source heat pump for heating and cooling. This provides insights on the systematic effects of ground source heat pump operation with regeneration with limitation on reaching negative temperatures at the bottom of the borehole, which can lead to ice formation, an increase in the volume of soil massive during freezing and destruction of pipelines. The article describes the change in the temperature of the soil mass under the operating conditions of a heat pump in two modes - stationary and with alternating "heat supply - cooling (air conditioning)" for long-term operation. Based on the obtained results it was revealed 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 soil massive temperature from the background value are reduced. The additional novelty aspect of modelling was obtained for the operating parameters of a geothermal source of energy with the account of long-term reversible operating mode of the heat pump. The energy balance model is well suited for the analysis of temperature in the bottom part of the geothermal boreholes was revealed for heating and air conditioning systems due to the non-stationary thermal loads determined by climatic conditions of the Ukraine and South-East Regions of Europe. The obtained results may serve as a new approach to optimization technical and economic indicators of geothermal boreholes during operation of the ground source heat pump operating with the account of reversible direction of heat flow for heating and cooling work modes to have continuous improvement of energy efficiency.

Keywords: Mathematical model of power systems; modes of operation; energy balance model; efficiency; ground heat pump; reliability

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1. INTRODUCTION, FORMULATION OF THE PROBLEM

Over half the country's electricity in the Ukraine is produced with nuclear power. The Ukraine produces all fossil fuels (in 2018: 14.4 Mtoe of natural gas and 2.3 Mtoe of crude oil), but million tons of oil equivalent [Mtoe] of coal, 16.5 in quantities insufficient to meet total energy demand. The Ukraine's energy mix is relatively diversified, with no fuel representing more than 30 % of the energy mix. In 2018, the share of coal (the country's primary fuel) dropped to 30%, followed closely by natural gas (28 %) and nuclear (24 %) [1].

The Ukraine depends on imports for around 83% of its oil consumption, 33% of its natural gas and 50 % of its coal.

In 2018 the Ukraine imported 8.5 Mtoe of natural gas, 13.8 Mtoe of coal and 10.4 Mtoe of oil products. Over half the country's electricity is produced with nuclear power. The Ukraine is the top energy consumer among EU countries. Its primary energy supply was 93 Mtoe in 2018, corresponding to around 90 % of Poland's consumption [1, 2].

Today, the Ukraine heavily depends on fossil fuels, which accounted for some 70 % of its primary energy supply in 2020. The Russian invasion has resulted in the occupation (the Zaporizhzhya nuclear power plant and about44% of total thermal power capacities) and destruction of critical energy infrastructure triggering a sharp decline in total energy supply, while electricity demand had fallen by 40% by October 2022.

In view of their high untapped potential in the country, bioenergy, hydro, solar and wind generation could constitute the building blocks of the Ukraine's future energy system, contributing up to nearly 80% of the total energy generation by 2050. Provided key strategies and investments are put in place, and complemented by nuclear, renewable could propel the Ukraine towards a carbon-neutral future. These are the main findings of the pathway scenarios developed by UNECE, based on it's the UNECE Carbon Neutrality Toolkit, published ahead of the Ukraine Recovery Conference (London, 21-22 June) [2, 3].

The Ukraine Energy scenario is substandard from the past few decades. The energy short-fall is around 4500 MW since the last five years [1, 2], [3] which is considered to be the hindrance in economic, scientific and technical growth.

2. LITERATURE REVIEW

District heating system 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 considerable (hence much gas is wasted) and operating costs are high, largely due to inadequate maintenance [3, 4]. The Ukraine has enormous untapped energy efficiency potential: although the end-use data are still limited, current indications are that energy efficiency potential is greatest in industry (34 % of the total), the residential sector (33%) and energy transformation at coal-fired power plants (22 %) [3]. Consumption in the residential sector – is compared with the EU benchmark of 90 kWh/m^2 of floor area. Because of climatic differences, the EU average cannot be used as a benchmark for residential efficiency in the Ukraine. In fact, consumption for heating, hot water and lighting per m^2 is higher even in energy-efficient countries with milder climates such as Denmark (142 kWh/m^2) and Germany (186 kWh/m^2).

Total final energy consumption in the agriculture, industry, construction, services and residential sectors, as well as energy transformation at fossil fuel decreased by 30.9 Mtoe (–36.4%) from 2012 to 2017. However, only one-third of this decline resulted from the energy efficiency improvements, with the remaining two-thirds stemming from a drop-in activity in 2014-2015 and structural changes within sectors (Fig. 1) [4]. The greatest energy efficiency improvements over 2012-17 were recorded in the residential sector (+22.7 %) and agriculture (+27.7 %), while the energy efficiency index for industry rose by 13.2 %. No energy efficiency improvement was recorded for fossil fuels energy trans-formation; in fact, it even decreased by 1%. Overall, energy efficiency improved to 12.5 % during 2012-2017.

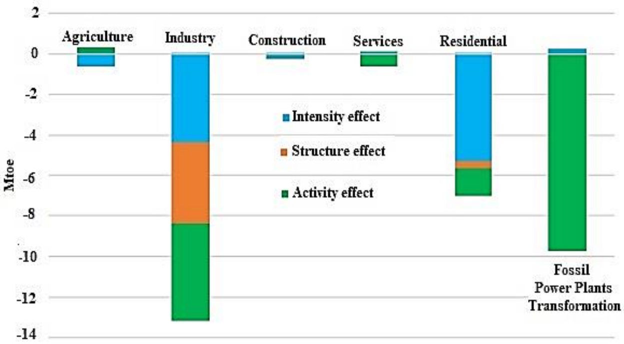

Fig. 1. **Ukraine energy consumption decomposition**
Source: **compiled by the authors**

Renewable energy accounted for 4.6 % of TPES in 2018: 3.4 % biofuels and waste, 1 % hydro and 0.2 % for other renewable power. The Ukraine experienced a renewable power deployment boom in 2018-19. The share of renewable power in the electricity generation mix increased by 3.6 times – from 1 % in 2015 to 3.6 % in 2019 [3].

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 (GHS) emissions. The buildings sector is the largest user of energy and CO_2 emission 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 [5] and more than 11 million housing units in the Ukraine [6]. Around 30% are built before 1940, around 45 % between 1950 and 1980 and only 25 % after 1980. 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-efficient and environmentally sound heating and cooling systems [7, 8]. The European Parliament adopted the Renewable Energy Directive, establishing a common framework for the promotion of energy from renewable sources [9]. This directive opens up a major opportunity for further use of heat pumps for heating and cooling of new and existing buildings. Therefore, the energy used to drive heat pumps should be deducted from the total usable heat. Furthermore, the EU member states must stimulate the transformation of existing building undergoing renovation into nearly zero-energy buildings.

In order to realize the ambitious goals for the reduction of fossil primary energy consumption and the related CO_2 emissions besides improved energy efficiency the use of renewable energy in the existing building stock have to be addressed in the near future [9, 10].

At present, the problem of energy saving can be solved both by assimilation of the in-novation technologies of generating, distribution, and consumption of energy [11]. The most efficient technology of the energy saving is the implementation of the heat pumps, due to their possibility to use a renewable energy sources (RES) for heating [12, 13], [14].

Following the above described problem: despite the need for application and numerous researches in the field of thermal energy, the wide implementation of the ground-source HP for regional conditions of the Ukraine and South-East Regions of Europe, is hindered by the insufficient efficiency of existing solutions enable to prevent freezing of the ground during long term of exploitation ground source heat pump (GSHP) systems which operate at the temperature of the outside air of t_0 = – 16…8 °C, typical for the South-Eastern Europe [10].

However, the works presented in literature, which describe the peculiarities of the use of the heating tools for the low-temperature water heating, ventilation and heat water supply, are insufficient [15, 16]. The foreign researches [17, 18], [19, 20], lack the methods, which would describe the alternative HPI and conditions of their practical application in the heat supplying systems with different heating units for the environmental conditions of the South-Eastern Europe. In [20, 21], the effect on the replacement rate by the scheme-construction solutions and operational modes of the alternative heat-supply system is not considered. Therefore, the issue of conditions of the efficient use of the heat pump technologies needs a systematic approach.

Our work differs from those foreign papers presented earlier in that this article analyzes the energy efficiency of the ground-source heat pump heating systems for energy saving technologies using models, results of numerical simulation of processes in GSHP and experimental studies for the South-Eastern Europe, which allows us to predict and prevent freezing of the soil around ground pipes and don't disturb vegetation.

This makes it possible to perform a rational choice of the conditions for the efficient operation of the heating system in winter period at the outside temperature of t_0 = –18…8°C typical for the South-Eastern Europe. This reduces the consumption of the hydrocarbon fuel in the structure of the heat balance of the regions and ensures the substantial energy saving and ecological effects in addition to those economical.

The attention payed by the foreign works [22, 23] 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 GSHP re-placing possibilities on the subsoil waters.

Heat pumps 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: water, air, soil. 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

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addition, heat pumps use environmentally friendly technologies with virtually no emissions of harmful substances into the environment [10].

Since today the issues of regulating the thermal regime of the soil massive through the rational organization of the processes of removing and supplying heat from the GSHP, as well as the issues of heat accumulation of the soil, are relevant, the analysis of factors influencing the thermal regime of the soil massive, and, as a consequence, the choice of its rational operating modes.

The purpose of the work is to predict the thermal regime of the soil massive through the rational organization of operating modes of the ground source heat pump and justifying rational conditions of implementation of the ground source heat pump for the climate conditions of the Ukraine and South-East Regions of Europe

3. MATHEMATICAL MODEL OF THE SOIL MASSIVE FOR DIFFERENT OPERATING MODES OF THE GSHP

The temperature field of the soil mass can change depending on operating modes. The characteristics of changes in temperature waves depending on the operating mode of the heat pump are considered in works [24].

It is known that when the installation operates only for heating or only for cooling, noticeable changes in the ground temperature background, which are reflected in the technical and economic indicators of the heat pump during of operation [26]. In this regard, in order to maintain the design parameters of the solar power plant and the thermal balance of the soil, it is necessary to combine the direction of heat flows, that is, the optimal mode is the alternation of “heating – air conditioning”.

Field studies have proven that when installing geothermal heat pumps, in the first year there is a significant load on the massive (significant changes in temperature are relative to the massive).

The first three years the well “runs in” (a slight continuous change in temperature), and then its depletion. The term “depletion” is understood by many authors as the operation of a well with a steady massive temperature on the casing wall, significantly different from the background massive temperature.

In most cases, field measurements are not applicable due to the inaccessibility of the research object located at a considerable depth.

3.1. Modeling the temperature field of the soil massive in the reversible mode of operation of heat pump

The actual operating schedule for a heat pump may vary for each property and region. When developing a mathematical model of the unsteady operating mode of a heat pump, the following features were taken into account:

– firstly, the heat flow is constantly changing according to a random law, determined by external factors, including climatic, technological features of equipment operation, etc.;

– secondly, 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. 2).

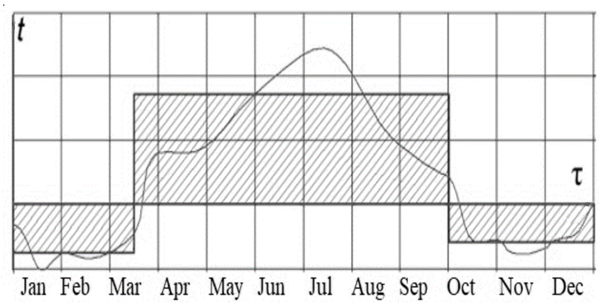

Fig. 2. **The averaged loads in the conditions of the problem being solved**
Source: compiled by the authors

3.2. Boundary conditions for the operation of a heat pump in heating – air conditioning mode

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 1st 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 conditions are:

$$t = t_0\ (r,\ \tau_2),\ \text{s} \qquad (1)$$

where τ_2 is the operating time of the heat pump installation of the third reverse mode period.

The soil temperature of the second reverse mode period:

$$t_1 = t\ (r,\ \tau),\ {}^0\text{C}\ . \qquad (2)$$

The soil temperature of the third reverse mode period:

$$t_3 = t\ (r_0,\ \tau),\ {}^0\text{C}\ . \qquad (3)$$

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:

$$\frac{\partial \text{t}}{\partial r}(\text{r}, \tau) = -\frac{q}{\lambda}. \qquad (4)$$

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

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

where q (τ) is 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 GSHP 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:

$$k_p = \text{Q}_{\text{in}}\ /\text{Q}_{\text{out}}, \qquad (6)$$

where Q_{in} is the amount of supplied flow during the cold season, W/m^2; Q_{out} is 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.

4. MODELING OF HEATING AND COOLING PROCESSES FOR OF THE HEAT PUMP WITH REVERSIBLE DIRECTION OF HEAT FLOW

Due to the reversibility of the working process, the heat pump can operate effectively both in heating modes 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 GSHP operating in the reversible mode are shown in Fig. 3a.

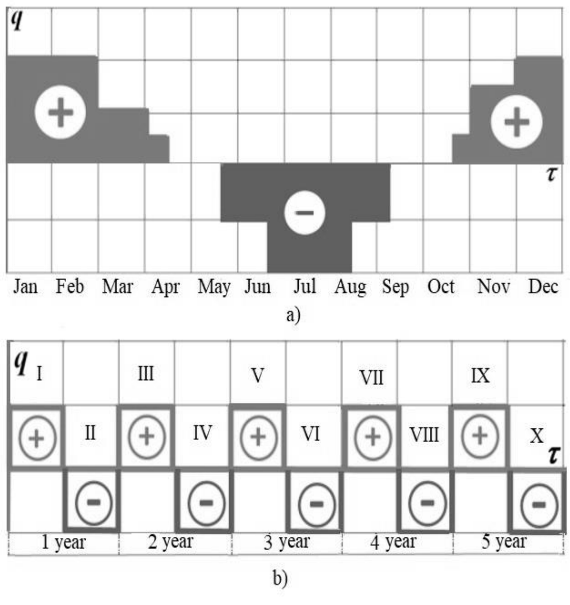

Fig.3. **GSHP loads in alternating mode:**
a – calculation model; b – main stages of heat pump operation:
I – 6 months; II – 1 year; III – 1.5 years; IV – 2 years; V – 2.5 years; VI – 3 years; VII – 3.5 years; VIII – 4 years; IX – 4.5 years; X – 5 years
***Source:* compiled by the authors**

The calculation conditions determine the alternation of periods when the heat pump is turned on (Fig. 3b) with periods of shutdown with a cyclicity determined by the time of year. The time to

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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. 3b 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].

5. SIMULATION OF THE TEMPERATURE FIELD UNDER AT REVERSIBLE DIRECTION OF THE HEAT FLOW WITH REGENERATION

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. 4 and Fig. 5) 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 Fig. 4.

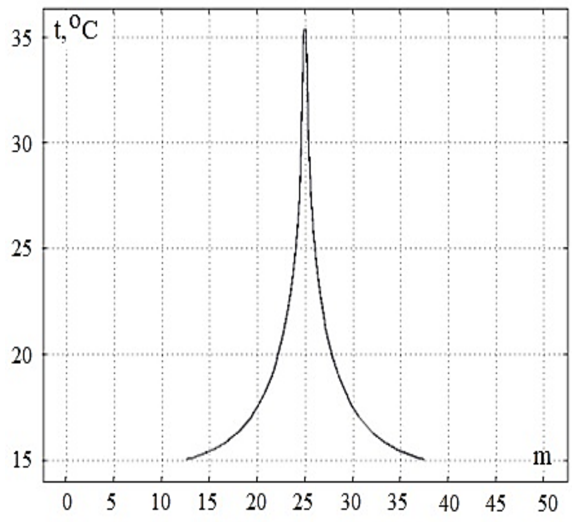

Fig. 4. **Temperature graph with positive thermal load during six months of the year**
Source: **compiled by the authors**

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. 5), 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.

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 1.5ºC.

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.

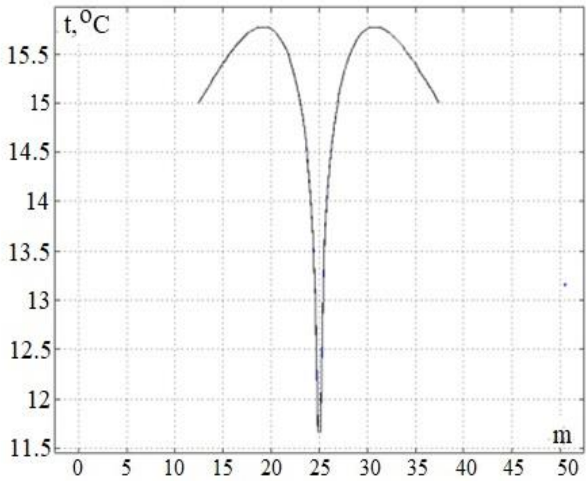

Fig. 5. **Temperature graph with alternating load on the of the soil massive during first year**
Source: **compiled by the authors**

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 k_p 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. 6.

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.

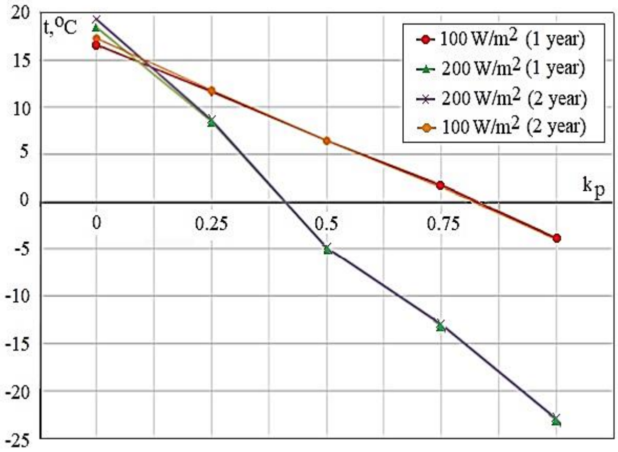

Fig. 6. **Dependence of soil temperature on the regeneration coefficient k_p**
Source: **compiled by the authors**

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 T_o, 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.

6. GENERALIZATION OF THE OBTAINED RESULTS INTO A CRITERIA EQUATION

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:

$$f = [Fo, \theta, Q]\ . \qquad (7)$$

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]:

$$\theta = \sum c \cdot Fo^n \cdot Q^m, \qquad (8)$$

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

Then the expression will look as:

$$\theta = f(k_p) \cdot (k_1 \cdot Fo^2 \cdot Q^2 + k_2 \cdot Fo \cdot Q + \ldots + k_n \cdot Fo \cdot Q), \qquad (9)$$

where: $f(k_p)$ is function taking into account the regeneration coefficient; $k_{1,2,\ \ldots\ n}$ is 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 is shown in the graph (Fig. 7). Numerical modelling was performed for Fo values from 4675 to 11686 and dimensionless active flow Q_1 = 2000 and Q_2 = 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].

7. METHODOLOGY FOR CALCULATING THE CHANGE IN TEMPERATURE OF THE SOIL MASS

A method for designing heat supply and air conditioning systems is proposed taking into account the long-term operation of a geothermal well and an analysis of the technical and economic parameters of the main design and technological solutions is presented. The procedure for performing calculations of the method is presented in Fig. 8.

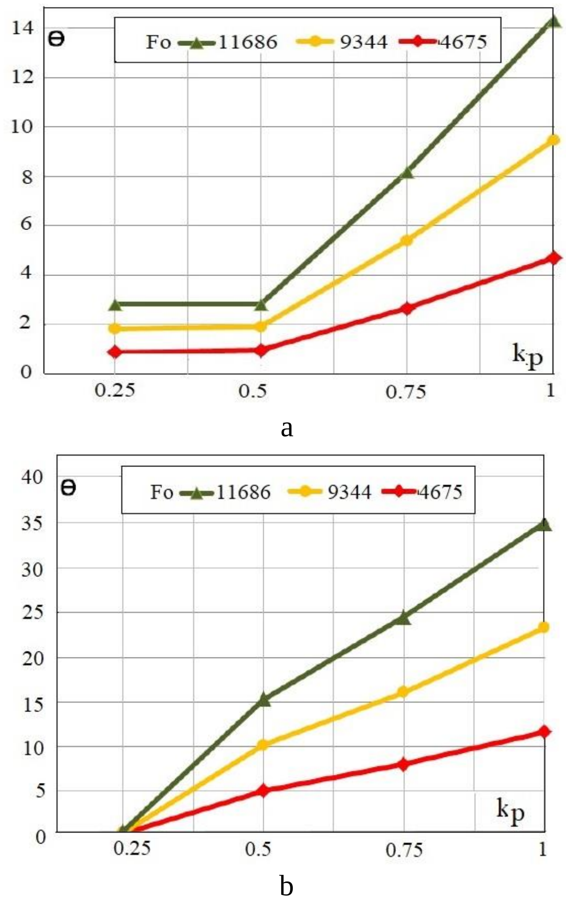

Fig.7. **Dependence of dimensionless temperature θ on regeneration coefficient k_p and dimensionless active flow Q in the range Fo from 4675 to 11686:**
a – Q_1 = 2000; b – Q_2 = 4000
***Source:* compiled by the authors**

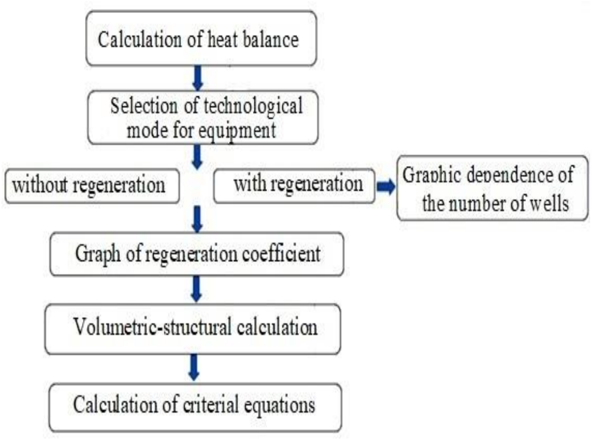

Fig. 8. **Calculation procedure**
Source: **compiled by the authors**

Data graphs for calculating the number of wells has been generated, taking into account the natural and climatic conditions of the design area and the results of soil studies (Fig. 9).

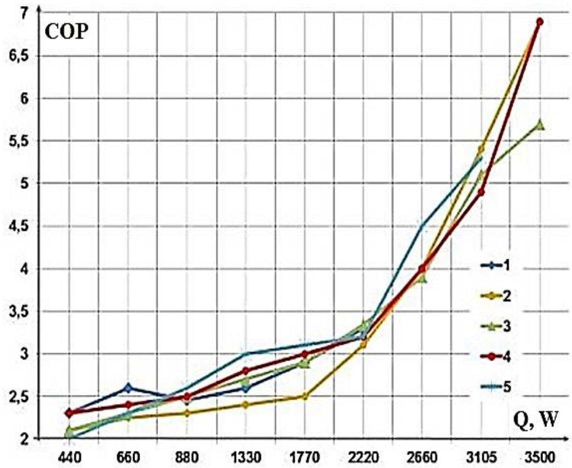

Fig. 9. **Dependence of the number of wells on the energy consumed by the heat pump with COP= 2**
Source: **compiled by the authors**

The calculation method allows identifying energy-efficient calculation execution at the design stage and forecasting the long-term operation of the heat pump over time. The design problem statement can be displayed in the form of a block diagram (Fig. 10).

The temperature of the well ground layer in the single-flow mode increases from the moment the heat pump is first switched on, and stabilizes in the 3rd year of operation.

During the downtime, the temperature decrease is compensated by the background heat flow and tends to the background temperature, but increases by an average of 2-3 ^{0}C, with the subsequent year of operation, the temperature increases and remains unchanged throughout the entire period. Reaching a quasi-stationary state is explained by the fact that the operating well is only a disturbing factor in the background temperature field of the Earth.

When supplied, the heat flow gives off heat to the well. After a break, the heat pump starts working with the parameters of the previous stage, namely, with an increased temperature of the formation, which has a positive effect on the operation of the HP.

In the alternating mode: it is obvious that when heat is removed, the formation cools down, and when supplied, it heats up, but the sequential reversal of the heat pump leads to the appearance of a system of thermal waves that cause a change in the well temperature and affect the technical and economic parameters of the equipment.

If the heat is removed from the soil massive, the temperature drops and after a couple of years it's established at some lower level. If supply and removal alternates, the temperature of the soil massive approaches to the background. If the regeneration coefficient equals 1, then the temperature of the soil massive is practically equal to the background.

CONCLUSIONS

1. A decrease in the temperature head in the bottom hole part of the geothermal well formation used as an alternative heat source in heating and air conditioning systems caused by non-stationary thermal loads determined by climatic conditions was revealed. The temperature of the well ground formation in the single-flow mode increases from the moment the heat pump is first turned on, and stabilizes in the 3rd year of operation. During the downtime, the decrease in temperature is compensated by the background heat flow and tends to the background temperature, but increases by an average of 2-3^{0}C, with the subsequent year of operation, the temperature increases and remains unchanged throughout the entire period. Reaching a quasi-stationary state is explained by the fact that the operating well is only a disturbing factor in the background temperature field of the Earth. When supplied, the heat flow gives off heat to the well. After a break, the heat pump starts working with the parameters of the previous stage, namely, with an increased formation temperature, which has a

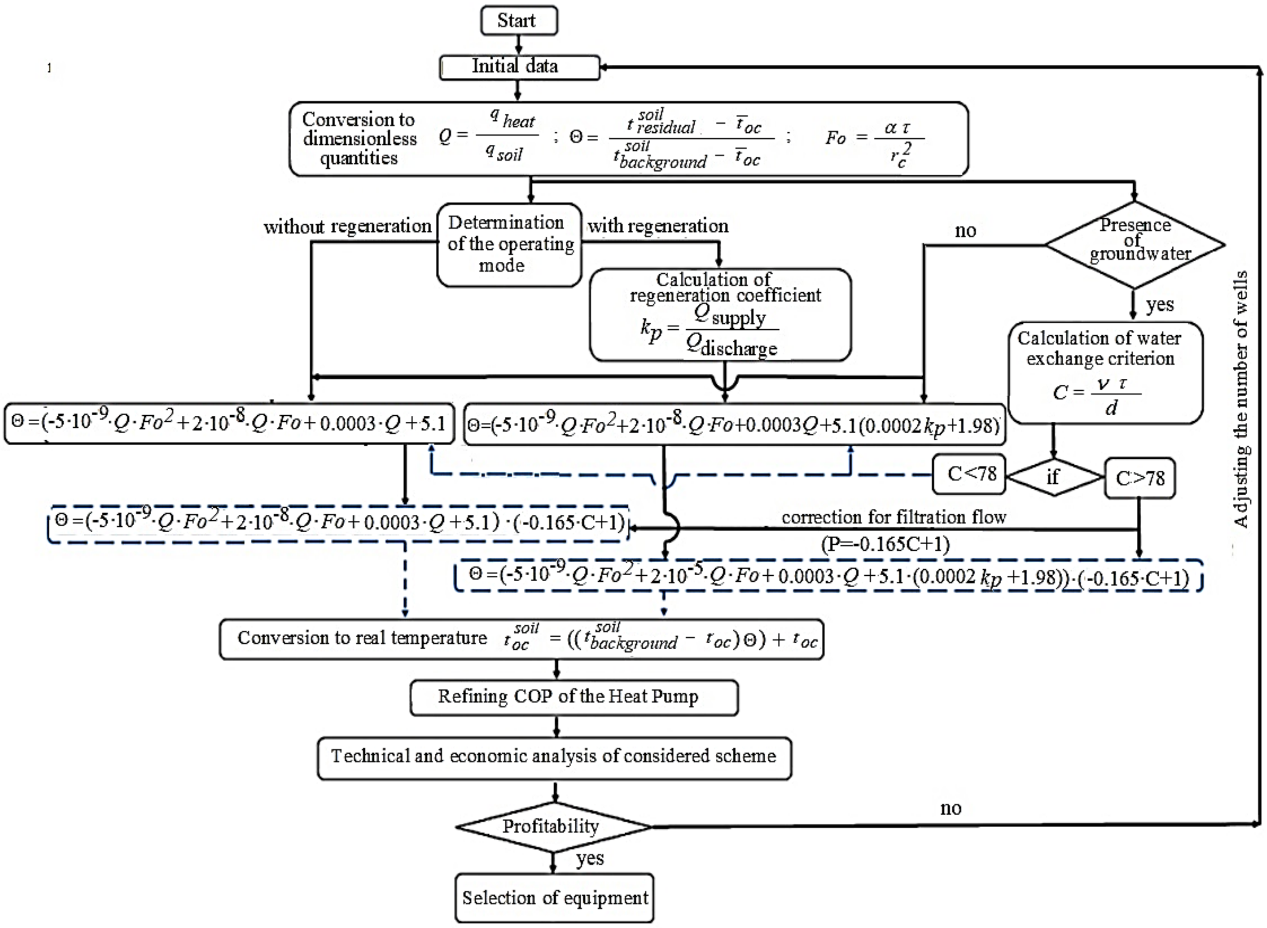

Fig. 10. **Diagram of technical and economic parameters for optimizing layout solutions for heating and air conditioning system using low-potential geothermal energy**

Source: **compiled by the authors**

positive effect on the operation of the heat power plant. In the alternating mode: it is obvious that when heat is removed, the formation cools down, and when supplied, it heats up, but the sequential reversal of the heat pump leads to the appearance of a system of thermal waves that cause a change in the well temperature and affect the technical and economic parameters of the equipment. The results of the study allowed us to come to the conclusion that the annual drop in ground temperature will gradually decrease under regeneration conditions. The regeneration process allows compensating for the "missing" values of the heat load. At the same time, the volume of the soil massif subject to changes in the temperature regime will expand every year. A positive fact is that in the regeneration mode, stabilization occurs earlier than in the single-flow mode.

2. The obtained results of the study of 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.

3. A methodology for designing heat supply and air conditioning systems using geothermal wells is developed. The method 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, which determine the dynamic change in the heat transformation coefficient of the installed heat pumps.

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Моделювання температурного поля в ґрунтовому масиві для різних режимів роботи ґрунтового теплового насоса

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АНОТАЦІЯ

У цій статті виконано моделювання впливу режимів роботи ґрунтового теплового насоса систем опалення та кондиціонування з використанням геотермального джерела енергії зі свердловини на температуру ґрунтового пласта навколо свердловини з урахуванням кліматичних умов України. Запропонована методологія моделювання ґрунтового теплового насоса, з урахуванням реверсивного напрямку теплового потоку для режимів роботи опалення та охолодження, є внеском у методи моделювання енергетичних систем. Кінцевою ціллю є отримання критеріальних залежностей для розрахунку робочих параметрів геотермальної свердловини та розробка методики проектування геотермальних свердловин з урахуванням їх тривалої експлуатації в циклічному режимі. Ідея, що лежить в основі методу, передбачає високу просторову та часову роздільну здатність, а також включення технічних деталей системи живлення та формування температури ґрунтового масиву ґрунту навколо свердловини для кліматичних умов України та Півдня. Східні регіони Європи. Новизна цього методу полягає в тому, що для аналізу різних оборотних режимів роботи ґрунтового теплового насоса для опалення та охолодження обрано використання параметричного підходу. Це дає уявлення про систематичні ефекти роботи ґрунтового теплового насоса з регенерацією з обмеженням досягнення негативних температур на дні свердловини, що може призвести до утворення льоду, збільшення об'єму ґрунтового масиву при промерзанні та руйнування трубопроводи. У статті описано зміну температури ґрунтового масиву за умов роботи теплового насоса в двох режимах – стаціонарному та зі змінним «теплопостачання – охолодження (кондиціонування)» для тривалої роботи. На основі отриманих результатів виявлено, що при роботі геотермальної свердловини зі змінним напрямком теплового потоку (з регенерацією) зменшуються віддалені наслідки експлуатації, пов'язані з відхиленням температури ґрунтового масиву від фонового значення. Отримано додаткову новизну моделювання робочих параметрів геотермального джерела енергії з урахуванням тривалого оборотного режиму роботи теплового насоса. Модель енергетичного балансу добре підходить для аналізу температури в придонній частині геотермальних свердловин, виявлено для систем опалення та кондиціонування повітря через нестаціонарні теплові навантаження, що визначаються кліматичними умовами України та південно-східних регіонів. Європи. Отримані результати можуть слугувати новим підходом до оптимізації техніко-економічних показників геотермальних свердловин при експлуатації ґрунтового теплового насоса, що працює з урахуванням реверсивного напрямку теплового потоку для режимів роботи опалення та охолодження, для постійного підвищення енергоефективності.

Ключові слова: моделювання енергетичних систем; режими роботи; модель енергетичного балансу; ефективність; ґрунтовий тепловий насос; надійність

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