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Modeling of thermal processes in vertical heat exchangers of ground-source heat pump

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ABSTRACT

The basic directions for perfection heat supply systems are the tendency of transition to the low-temperature heating systems based at application heat pump installations. We consider heat supply systems with ground-source heat pump. The paper considers modeling the efficiency of ground-source heat pumps with the account of Ukrainian climate conditions. The paper presents the energy performance criteria which show the way to rational implementation of ground-source heat pumps for heating. A computational model based at non-stationary heat exchange processes in elements of ground-source heat pumps is developed. Generalization and analysis of theoretical and experimental dates allow establishing nature of dependence thermophysical properties on temperature in soil around ground heat exchangers during long term operation of the system. Numerical simulation of thermal processes in vertical ground pipes for ground-source heat pump working with low-temperature heating systems has been worked out. The results of numerical modeling demonstrated perfection and technical adaption of ground-source heat pump for low-temperature heating systems with rational using ground energy potential. The novelty of our method is complex usage theoretical and experimental results which enable to prevent freezing in the ground during long term exploitation This provides insights at effects of different resource mixes and may serve as a new approach to analysis of future heat pump systems using ground source energy development. The proposed method contributes to the field of creation and implementation the sustainable heating technologies using renewable energy sources. The ground heat exchange pipes quantities that are necessary for effective operation heat pump installation, capacity and coefficient of performance with the account of climate conditions are calculated.
Keywords: Efficiency; reliability; numerical simulation, ground-source heat pump, ground pipe, low-temperature heating

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1. INTRODUCTION, FORMULATION OF THE PROBLEM

The global requirement for sustainable energy provision and a political imperative for energy independence of Ukraine have combined to increase interest in the use of renewable energy sources to meet growing energy demands [1, 2]. Therefore, the heat pump (HP) system introduces a new path for sustainable systems with clean energy supply and improved energy efficiency [3, 4]. Current power systems are still dominated by fossil fuel-based generation of energy. At present, the problem of energy saving can be solved both by assimilation of the innovation technologies of generating, distribution, and consumption of energy [5, 6], [7]. The most efficient technology of the energy saving is the implementation of the heat pumps [8, 9], [10], due to their possibility to use a renewable energy sources (RES) for heating [11, 12].

The increase in prices for gas, which is used for heating, leads to permanent increase of prices for domestic and communal services. Moreover, natural gas reserves are finite and concentrated mainly in foreign countries. Only 10...20 % of fuel demand is covered in Ukraine by national sources [13, 14]. The experience of foreign countries shows, that using of heat pumps for low-power heating technologies, allows to reduce significantly using if organic fuel. Implementation of renewable energy sources makes it possible to reduce the cost for heating and air conditioning of consumers. One of the most promising directions for the development of alternative energy is the use of heating systems based on heat pumps that use low-potential ground and subsoil energy [13, 14], [15]. The reason of high efficiency HP are explained by the fact that, unlike machines that use the Carnot cycle, heat pumps use the heat that is released in a highly efficient phase transition. Operating experience shows that with a scientifically based design of heat pump heat supply systems with renewable energy sources, the prospects of these systems are obvious: the service life is at least 30…40 years, and such a system can pay for itself in 3-5 years [6, 8].

To combat global warming and to address the fossil fuel scarcity, a shift to less carbon intensive resources in energy supply is necessary [1, 9].

The power sector plays a central role in the decarbonization of the energy sector. Today, more than 40 % of energy-related carbon emissions stem from the power sector [12].

Especially in Ukraine, where ambitious greenhouse gas emission reduction targets have been legislated, renewable energies play a key role. Ground energy are bound to be the most important source in climate conditions of Ukraine [15], the observed growth rates, but also the existing support schemes [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 Ukraine, is hindered by the insufficient efficiency of existing solutions enable to prevent freezing of the ground during long term of exploitation GSHP;

Thus, **the purpose of this study** is perfection of energy efficiency of the ground-source heat pump heating systems for energy saving technologies using models, results of numerical simulation of processes in GSHP which allows to predict and prevent freezing of the soil around ground pipes and don't disturb vegetation.

2. LITERATURE REVIEW

The performed analysis shows that insufficient attention is paid to theoretical and experimental research aimed at increasing the efficiency of thermal processes in elements of heat pump systems of alternative heat supply using ground energy, soil waters and waste waters of industrial enterprises.

There are no mathematical models and methods for determining the parameters of industrial and individual heat supply systems based on GSHP using soil energy, which can prevent freezing of the soil around ground pipes and don't disturb vegetation.

Currently, in Ukraine and abroad, the heat pump system of decentralized heat supply is insufficiently researched; there is little information about rational modes of operation based on energy-saving technologies. The analysis of literary sources showed that the use of soil energy, which is a limitless accumulator of low-potential energy, is promising for alternative heat supply systems. But the energy potential of the soil energy source is insufficiently disclosed, and there is no methodology for calculating the ground-source heat pumps (GSHP), taking into account such ecological requirements as: prevention of freezing of the soil layer and elimination of damage for vegetation.

Model features. The existing method is imperfect due to the fact that the thermophysical properties of the soil differ for different regions of the operation of the heat pump system, in addition, soil moisture, temperature and chemical composition, and, therefore, its thermal conductivity can differ significantly, so even closely located heat pipes can have different indicators of work efficiency, and long-term use of GSHP with ground pipes (GP) can cause freezing of the soil layer around the GP and cause damage of plants.

The calculation method proposed by us is based on a mathematical model of thermal processes in GSHP, where the ecological factor is taken into account – the prevention of freezing of the soil layer around the GP.

When working with a HP with a GP (Fig. 1), an important factor is the deepening of the HT. For the south and north of Ukraine, the depth of the HT installation is 5 m and 10 m, respectively, because the temperature at such a depth does not depend on climatic conditions and is 11 ºC.

Experimental study of dependence between thermal power and temperature field in soil as a function of its moisture content and particle size composition for vertical heat-absorbing ground pipes the experimental stand was carried out (Fig.1).

Thermophysical properties of heat carrier – 30 % mixture of water and glycol are: c_p=3.82 kJ/(kg K), $v = 107.5\cdot10^{-4}$ m^2/s, $\lambda_B = 0.503$ W/(m·K), ρ_B= 1040 kg/m^3. Experiments have got several stages for different moisture W = 5…20 % and density ρ_B =1400…2000 kg/m^3, in accordance with the granulometric composition of the soil [13, 14].

Generalization and analysis of experimental data made it possible to establish the dependence of thermophysical properties of the soil from temperature (Fig. 2) [14].

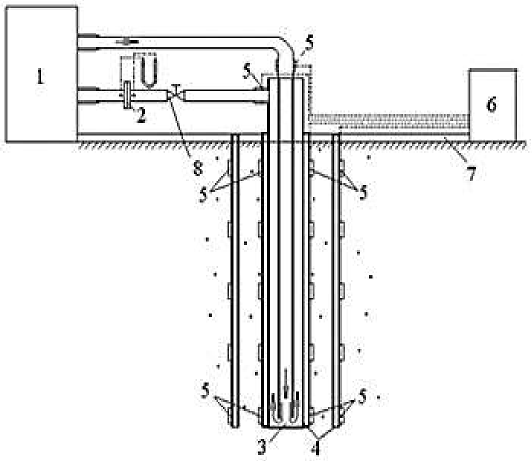

Fig. 1. **Scheme of the experimental stand: 1 – thermostat; 2 – flow meter; 3 – ground pipe; 4 – pipes with thermocouple wires; 5 – thermocouples; 6 – millivoltmeter; 7 – thermal insulation of soil area; 8 – regulating valve**
***Source:* compiled by the authors**

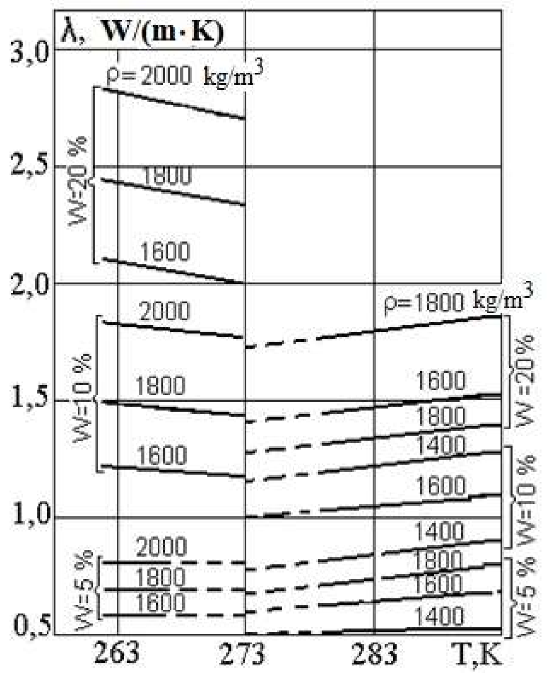

Fig. 2. **Thermophysical properties of the soil**
***Source:* compiled by the authors**

It is determined that the proposed GSHP are perspective for Ukraine which has the deficit of own energy resources, as enables to increase the replacement factor of organic fuel and reduce the amount of thermal effluent to the environment.

Analysis of the temperature gradient around the ground pipe. A large number of GSHP have been used in residential, commercial and publish buildings throughout the world due to the attractive advantages of high energy and environmental performances. These buildings represent the biggest potential for energy saving technologies.

As a further development of our investigation [13], the changes of temperature gradient in the soil around the ground pipes (GP) as the hot source of energy for heat pump cycle are analyzed (Fig. 3). The temperature gradient depends of depth and the temperature gradient of the soil changes most dynamically at a depth 4…8 m. At a depth of 8…12 m, the soil temperature decreases from 9 ºC to 8ºC. The isotherms in the soil run parallel to the ground's surface. According to the results of research [14], during some period of time after start of operation of the HP, the temperature gradient changes significantly at a distance 0.1 m near ground's surface (Fig. 4). The temperature around the buried ground tube does not raise more than 9.0 ºC although before the ground pipes (GP) are buried, the temperature at the corresponding depth reached 12ºC.

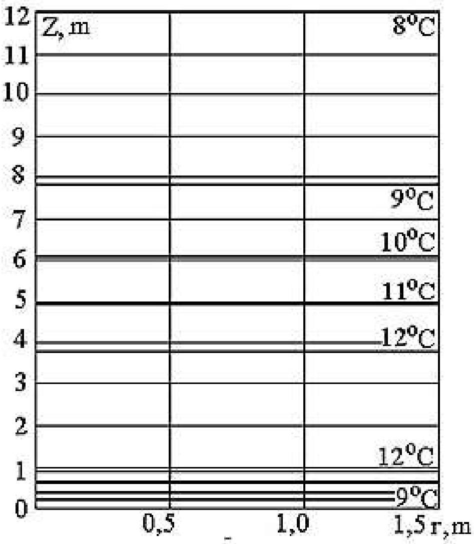

Fig. 3. **Distribution temperatures at the beginning of ground-source heat pumps operation**
***Source:* compiled by the authors**

At distance 1 m under soil, temperatures almost don't change comparably to isoclines' at Fig. 4. Therefore, for the normal operation of the GP for GSHP, it is necessary according to results of calculation [13,14] to reduce the temperature at the inlet to the compressor to 7°C. Overheating of the working fluid by 2 °C must be ensured in order to prevent drops of fluid from entering the compressor.

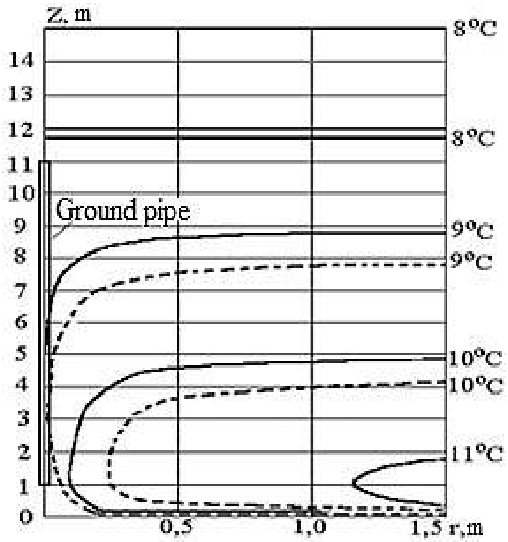

Fig. 4. **Distribution of ground temperatures around ground pipes during the operation of ground-source heat pumps**
Source: **compiled by the authors**

As it can be seen from Fig. 3 and 4 that after the start of operation of the GSHP with vertical pipes, distribution of temperature in the soil around GP changes sharply. And the biggest effect is observed at distance 1.5 m. Therefore, in case of several closely located GP, the distance between them should be 2 m.

Numerical simulation of thermal processes in the vertical ground pipes of the ground-source heat pump.

For determination of thermophysical properties of working fluid of GSHP, the RETScreen [15] and CoolPack 1.49 software packages are used [16]. CoolPack is a collection of easy-to-use programs for modeling and design of various HP systems. To carry out calculations, it is necessary to specify only units of measurement and key points, and there is no need to describe the operating diagram of the device.

The programs in CoolPack cover the following modeling purposes:

– calculation of properties (thermodynamic and thermophysical data);

– cycle analysis – for example, comparison of one- and two-stage cycles;

– determination of system dimensions - calculation of component sizes from general criteria;

– system modeling – calculation of operating conditions in a system with known components;

– process assessment – assessment of the efficiency of the system and proposals for reducing energy consumption;

– compound calculations - calculation of compound processes;

– modeling of the transient cooling process of an object – for example, to estimate cooling periods.

The use of the described software package CoolPack 1.46 allows getting an idea of thermophysical properties not only individual working fluids, but also their mixtures in various proportions.

Using CoolPack 1.49 for numerical modeling [16], the heat pump cycle (Fig. 5) was calculated for the new parameters with a temperature in the hot spot of 60 ºC; working substance of cycle is ammonia.

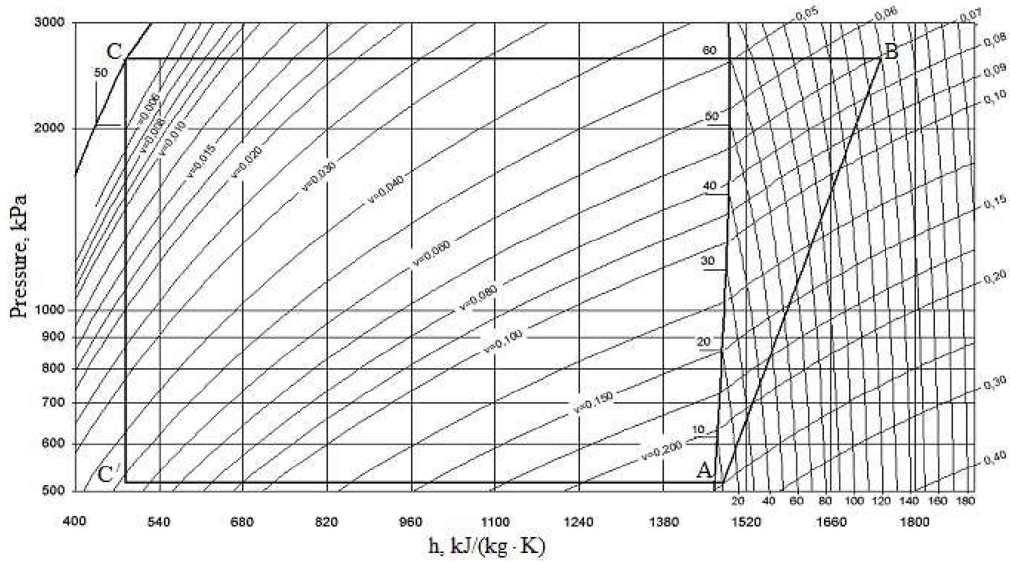

Fig. 5. **Ground-source heat pumps cycle with ground pipes using CoolPack**
A – start of compression; B – output of compressor; C – condensation point of the working fluid
Source: **compiled by the [5, 6]**

Italics show the process in which the temperature in which the temperature of the working carrier at the outlet of the GP was 10 °C.

For this cycle (Fig. 6) coefficient of transformation calculated in accordance to formula:

$$COP = COP' \cdot \eta_i \cdot \eta_{до} , \quad (1)$$

where COP' = $(h_B–h_C)/(h_B–h_A)$ is coefficient of transformation without taking into account of compressor and isentropic influence; (h_B-h_C) is difference of enthalpies in points B and C; (h_B-h_A) is difference of enthalpies in points B и A; $\eta_i = 0.7$ is isentropic efficiency; $\eta_k = 0.92$ – efficiency of the compressor.

Coefficient of performance is defined by equation using equation (1) is equal:

$$COP' = (1720-480)/(1720-1480) = 5.2; \quad (2)$$

$$COP = 5.2 \cdot 0.9 \cdot 0.92 = 4.3. \quad (3)$$

The value of COP=4.3 is significantly higher than the typical values given in [17, 18], [19], which indicates the high efficiency of the cycle in Fig. 3.

3. METHOD OF NUMERICAL SIMULATION OF THERMAL PARAMETERS IN GROUND HEAT EXCHANGER

Using object-oriented programming facilities numerical modeling of amount of heat Q that can be provided by one GP [19, 20]. For 8 points of section C`–A (Fig. 6) the input data for further calculations were determined, and these indicators were averaged for each section. Thus, the GP was divided into 10 height sections, for each of which Q was calculated using the algorithm below.

In refined calculations, the average value of the parameters between two extreme points of section calculated at the current moment. The following thermophysical properties were averaged: dynamic viscosity, density, coefficient of thermal conductivity and heat capacity.

The area of the innertube channel:

$$F_0 = \left(d^2_{зов} - d^2_{внутр}\right) \cdot \frac{\pi}{4}, \text{ m}^2, \quad (4)$$

where $d^2_{зов}$ i $d^2_{внутр}$ are diameters of the outer and inner pipes, respectively, m.

The mass flow of the coolant in the inter-pipe channel, kg/s [14]:

$$W = u \cdot \rho \cdot F_0, \text{ kg/s}, \quad (5)$$

where u is velocity of the liquid flow, m/s; ρ *is* density, m^3/kg; F_0 *is* area of inter-pipe channel, m^2.

The hydraulic diameter from formula (3) is equal:

$$d_г = \sqrt{\frac{F_0 \cdot 4}{\pi}}, \text{ m}. \quad (6)$$

The surface area of the outer pipe, which receives the flow of heat from the soil around GP [13]:

$$F = d_{зов} \cdot \pi \cdot l, \text{ m}^2, \quad (7)$$

where l is step of modeling, m.

Kinematic viscosity of flow:

$$\nu = \frac{\mu}{\rho}, \text{ m}^2\text{/s}, \quad (8)$$

where μ *is* dynamic viscosity of liquid, kg/(m·s).

Thermal diffusivity:

$$a = \frac{\lambda_p}{C_p \cdot \rho}, \text{ m}^2\text{/s}, \quad (9)$$

where λ_p is thermal conductivity, W/(m·K).

Reynolds number:

$$\mathrm{Re} = \frac{u \cdot F_0}{\nu}. \quad (10)$$

Prandtl number:

$$\mathrm{Pr} = \frac{\nu}{a}. \quad (11)$$

Criterion equation for forced convection in channels of ground pipes [14].

For a laminar flow the Nusselt numberwith the account formulas (8)-(11) [13]:

$$Nu = 1{,}86 \cdot \left(\frac{n_f}{n_w}\right)^{0{,}14} \cdot \left(\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot d_г}{l}\right)^{0{,}33}, \quad (12)$$

where n_f, n_w – dynamic viscosity of at average temperature of the fluid and the GP wall, respectively.

For small flow rates of the coolant:

$$\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot d_г}{l} \le 4{,}5. \quad (13)$$

For equation (13) Nusselt number is equal:

$$Nu = 0{,}5 \cdot \frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot d_г}{l}. \quad (14)$$

For

$$4{,}5 \le \frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot d_г}{l} < 13. \quad (15)$$

Nusselt number is equal:

$$Nu = 1{,}62 \cdot \mathrm{Re} \cdot \mathrm{Pr} \cdot \left(\frac{d_г}{l}\right)^{0{,}33}. \qquad (16)$$

For correct calculation of Nu, the program implements processing of the following parameter:

$$\frac{\mathrm{Re} \cdot \mathrm{Pr} \cdot d_г}{l}. \qquad (17)$$

Depending of result, the appropriate equation is used. After determining all necessary data, the value of the heat transfer coefficient for the working fluid can be calculated:

$$\alpha_{p.m.} = \frac{Nu \cdot \lambda_p}{d_г}, \text{ W/(m}^2\text{·K)}. \qquad (18)$$

The value of thermal resistance of the soil [14]:

$$\frac{1}{\alpha_{гр.}} = \frac{F \cdot \ln\left(\frac{4 \cdot l}{d_{зов}}\right)}{2 \cdot \pi \cdot l \cdot \lambda_{гр}}, \text{ (m}^2\text{·K)/W}, \qquad (19)$$

where $\lambda_{гр}$ is estimated (Fig 2) value of thermal conductivity of the soil.

As a result, the heat transfer coefficient [14]:

$$k = \frac{1}{\frac{1}{\alpha_{p.m.}} + \frac{\delta_{cm}}{\lambda_{cm}} + \frac{1}{\alpha_{гр}}}, \text{ W/(m}^2\text{·K)}. \qquad (20)$$

Based on the obtained data, the amount of heat flow that can be received by working fluid on the section with the account equations (5), (7), (20):

$$Q = F \cdot k \cdot \Delta t, \text{ W}, \qquad (21)$$

where Δt is difference of temperature, K.

The total heat is calculated as the sum of heat for each section.

RESULTS OF NUMERIC SIMULATION

Results of numeric simulation obtained using refined calculation [17] based at new data that are shown in Fig.6.

The graph of the change in heat obtained by the corresponding segment of the GP is shown in Fig.7.

Analysis of specified results of numerical simulation shows that the total amount of utilised heat by one ground pipe is equal according to equation (21):

Q = 67,4 W.

Preliminary calculations by simplified methodology [13] give an overestimated value Q = 90 W.

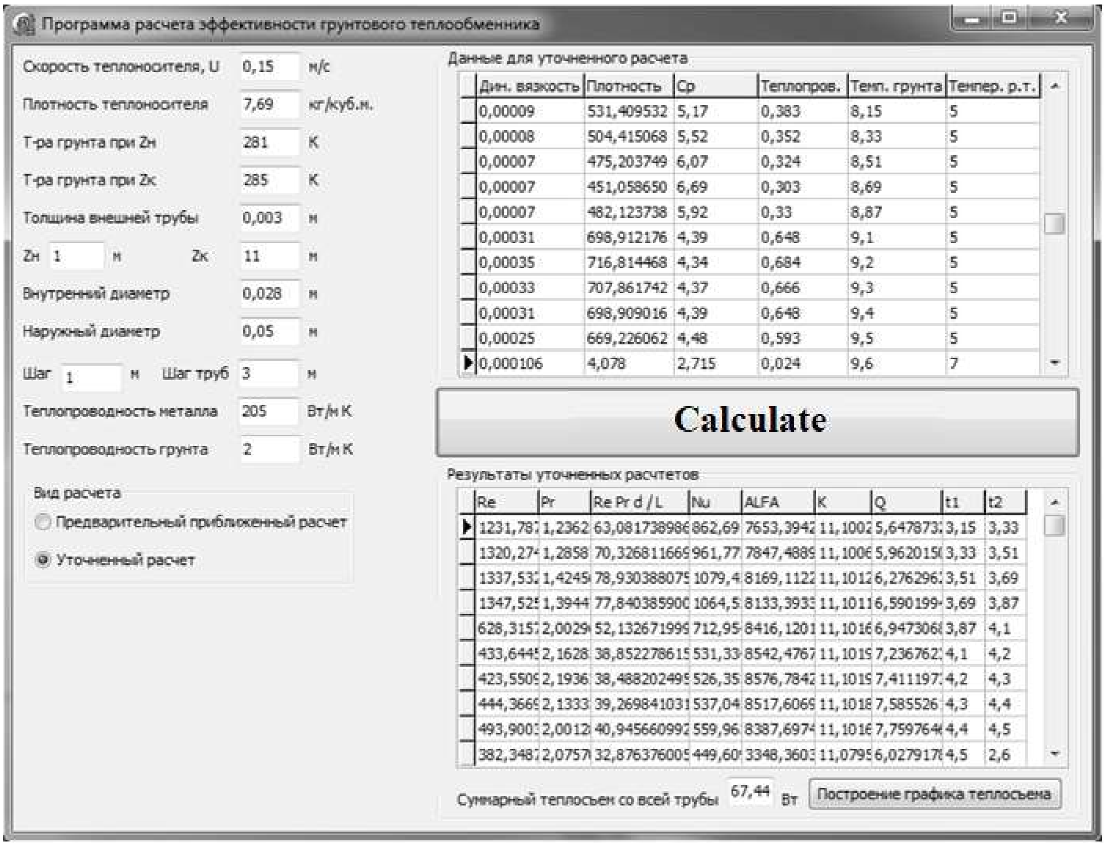

Fig. 6. **Refined results of numeric modeling**
***Source:* compiled by the authors**

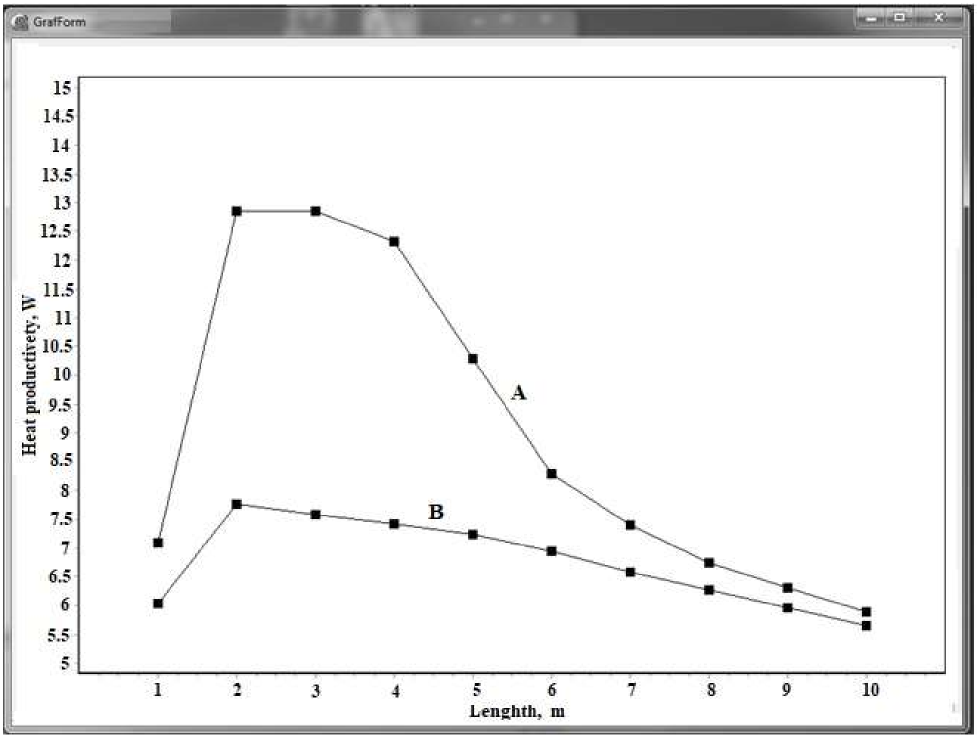

Fig. 7. **Dependence of heat on lengths of ground pipes**
A – at the beginning of operation ground-source heat pumps;
B – during the operation of ground-source heat pumps
***Source:* compiled by the authors**

Changes of temperature gradient led to a significant decrease of heat energy utilised in each section of ground pipe and negatively affected the total amount of heat, which is decreased by 25 %.

It should be noted that in the first approximation, the nature of the curves (Fig. 7) not change, but curve B is less inclined.

For ground-source heat pumps using low-potential heat of soil, the distance between GP must be no less than 2 m in order to prevent their mutual negative influence at the soil. This solution prevents freezing of the ground during long term of exploitation GSHP.

Changes of temperature field of the soil are determined according to [13], during operation and after GSHP was taken out of operation (Fig. 8) [13, 14]. At the end of the heating season, when number of GP n < 6, the temperature of the soil around GP drops to 0ºC, which is a threat of freezing of surrounding soil.

The results of numeric simulation of change the field of temperature at depth 7 m, performed at 12-hour intervals during the operation of the GP for 48 hours (Fig. 9).

Without heat extraction, the temperature of soil increases, which (Fig. 10). For the specified case, the change of the temperature field in the soil around the soil pope at the depth 7 m is shown after the soil system was taken out of operation, every 12 hours during 48 hours, when the GP is out work.

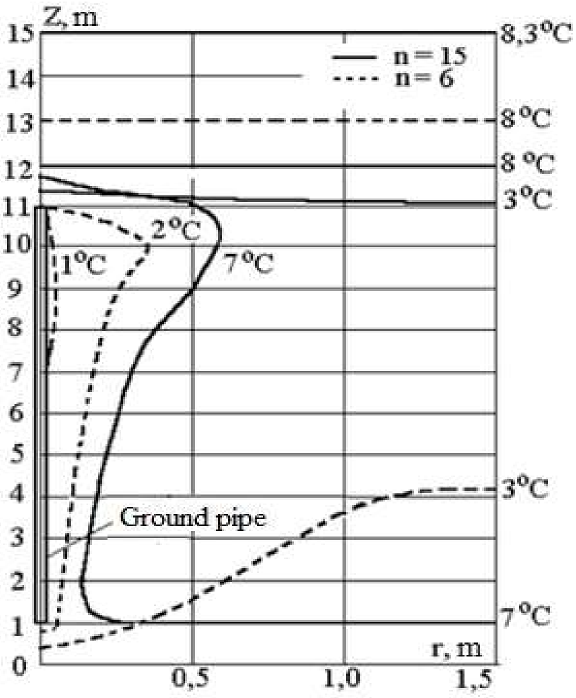

Fig 8. **Field of temperature at the end of heating season**
***Source:* compiled by the authors**

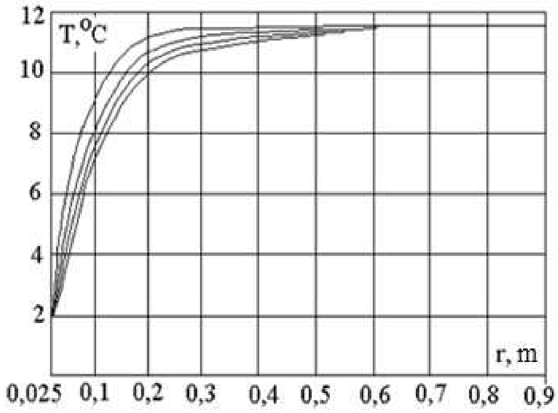

Fig. 9. **Non-stationary field of temperature of soil around ground pipes during operation of ground-source heat pumps**
Source: **compiled by the authors**

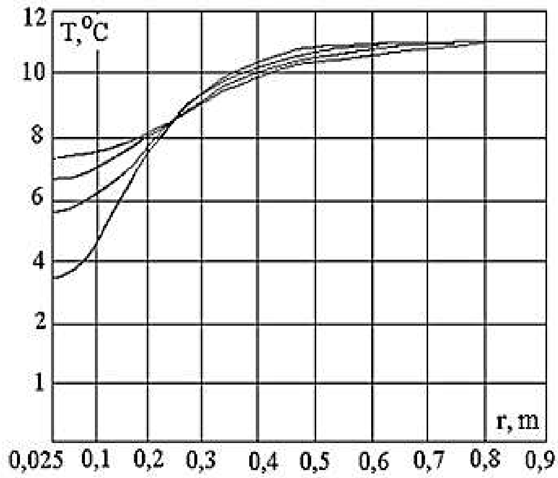

Fig.10. **Non-stationary field of temperature of soil around ground pipes after taking out of operation ground-source heat pumps**
Source: **compiled by the authors**

Table 1 show results of numerical simulation, by using which the average heat transfer coefficient is equal $k = 0.72$ W/(m^2·K).

Table 1. **Output of heat from single ground pipe**

Parameters of coolant		
Coolant	R717	Ammonia
Velocity, U	m/s	0.15
Density, ρ	kg/m^3	7.69
Heat capacity, C_p	kJ/(kg·K)	4.94
Thermal conductivity, λ	W/(m·K)	0.42
Inlet temperature, $T_{вх}$	°C	5.00
Outlet temperature, $T_{вых}$		10.00

Source: **compiled by the authors**

Table 2. **Parameters of ground heat exchanger**

GT parameters		
Pipe length	m	10
$Z_н$	m	1
$Z_к$	m	11
$d_{нар}$	m	0.05
$d_{внутр}$	m	0.028
Step	m	1
Material	aluminium	
Thermal conductivity	W/(m·K)	205
Thickness of outer pipe	m	0.003

Source: **compiled by the authors**

5. CONCLUSIONS

The widespread implementation of GSHP with ground heat exchangers is hampered by rational design of the evaporation part and preparation of wells for them. For example, on Odessa region, evaporation zone of the coolant in ground popes should be at the depth 5 m. That is, the height of the buried part of the GP must be about 7…10 m, depending on the thermal load, the coolant and operating pressure. This plays a significant role in the cost of GSHP heating system.

In addition, during long-term operation of the GSHP, there can be noticeable decrease in the temperature field around the evaporator is observed until a column of frozen soil appears, and the radius of this column and the rate of its increase directly depend on the amount of heat removed by the HP, i.e. on the amount of heat given off by the soil. This is dangerous not only because of the disruption of vegetation, but also because of a possible decrease in the strength of the foundations of nearby buildings.

However, such negative impacts can be mitigated by installing heat accumulators and using comprehensive alternative heat supply systems [18, 19], [20].

The second impact factor is that the heat transfer capacity of the soil at the point of the planned installation of GSHP can be deter-mined only by additional experimental research and further numerical simulation. Because the soil moisture, temperature, composition and thermal conductivity can change significantly during the heating season. Therefore, ground pipes, even closely located ones, can have completely different performance indicators.

Our research is carried out to optimize the design of ground pipes pf GSHP [21]. Modelling of heat exchange processes in the ground around GP shows that in order to avoid soil freezing, the minimum permissible number of evaporators is equal 6. Installation 8…15 heat exchangers of GSHP allows to avoid seasonal temperature fluctuations near ground pipe.

However, even without improving ground heat exchangers, it is clear that they have an advantage compared to solar collectors because:

– ground heat exchangers don't require significant areas for installation;

– performance ground heat exchangers is practically independent of weather conditions and is characterized by high stability;

– ground heat exchangers are more reliable.

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Моделювання теплових процесів у вертикальних теплообмінних трубках грунтового теплового насосу

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АНОТАЦІЯ

Одним із основних напрямів удосконалення систем теплопостачання є тенденція переходу до низькотемпературних систем опалення шляхом застосування теплонасосних установок. В роботі основна увага зосереджена на удосконаленні теплових параметрів і схемно-конструктивних особливостей елементів теплонасосної системи теплопостачання з використанням енергії ґрунту. Для цього застосовано інструментарій математичного моделювання процесів в ґрунтових теплових насосах з урахуванням кліматичних умов України. У статті наведено критерії енергетичної ефективності, які показують шляхи раціонального застосування ґрунтових теплових насосів для теплопостачання промислових і індивідуальних споживачів. Розроблено розрахункову модель нестаціонарних процесів теплообміну в елементах ґрунтових теплових насосів. Шляхом числового моделювання визначені оптимальні технічні параметри теплонасосної системи з ґрунтовими теплообмінниками. На основі узагальнення та аналізу теоретичних та експериментальних результатів дослідження встановлено характер залежності теплофізичних властивостей джерела енергії для теплового насосу та зміни температурного поля в грунті навколо ґрунтових теплообмінників під час тривалої експлуатації системи. Виконано чисельне моделювання теплових процесів у вертикальних ґрунтових трубах теплового насоса, результати якого підтвердили високу надійність технічної адаптації ґрунтового теплообмінного контуру теплового насосу для систем низькотемпературного опалення для раціонального використанням енергії ґрунту. Новизна нашого інструментарію полягає в комплексному використанні методів числового моделювання та експериментальних результатів, які дозволяють попередити явище промерзання ґрунту навколо ґрунтових трубок при тривалому періоді експлуатації системи. Визначено граничні параметри впливових чинників, які попереджають негативний вплив теплонасосної системи на довкілля, можна вважати можна інноваційним підходом до створення надійних теплонасосних систем, які раціонально використовують природні ресурси, що позитивно впливає на розвиток паливно-енергетичного комплексу. Запропонована методологія сприяє створенню та впровадженню технологій надійного теплопостачання з використанням відновлюваних джерел енергії.

Ключові слова: ефективність; надійність; чисельне моделювання; ґрунтовий тепловий насос, ґрунтова трубка, низькотемпературні системи опалення

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