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REGULAR ARTICLE

Regulations of the Formation of the Thermal Influence Zone of Underground Heat Exchanger as an Environmental Risk Factor for the Soil Environment

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The task of establishing the regularities of creating a thermal area in the soil when using heat exchangers of secondary energy sources is considered. The characteristics of the non-stationary process of spreading thermal energy in the soil and related information about the degree of cooling of the energy carrier in the process of forming the temperature range and the duration of the process are important issues considered in the process of implementing the task. The study of these regularities makes it possible to assess not only the energy efficiency of the use of secondary energy sources, but also their environmental safety for the underground environment. An analytical approach to solving a problem requires the creation of a mathematical model and a methodology for its implementation. A mathematical model is proposed, which is based on the differential equation of non-stationary thermal conductivity in a two-dimensional formulation and is supplemented with initial and boundary conditions that characterize the real process of thermal area formation. The implementation of the mathematical model was carried out by the method of using integral transformations, in particular, Lapass and Fourier transformations were applied. As a result, an analytical solution was obtained, which made it possible to evaluate the characteristic regularities of the process. To obtain numerical solutions and their analysis, we will use the concept of dimensionless time. Numerical implementation of the problem for various conditions allows to establish the degree of dissipation of heat energy in the soil, which is estimated by the coefficient of the useful effect of the system, and to establish the duration of the process of formation of the thermal area.

Keywords: Thermal pollution, Heat exchange, Mathematical model, Thermal soil degradation, Thermal area, Ecological risk, Groundwater

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1. INTRODUCTION

The use of secondary energy sources on an industrial scale is often associated with the operation of heat exchangers for energy exchange between heat carriers. In cases of operation of underground heat exchangers, part of the energy is dissipated into the ground, forming a temperature field. The formation of the area of the thermal field around the working heat exchanger is accompanied by the dissipation of energy into the environment, which worsens the economic and ecological performance of the system. In order to substantiate the measures aimed at the protection of the underground soil and water basin, it is necessary to have a reliable forecast of the change in time of the thermal energy situation in the zone of influence of the heat exchanger. In this regard, it is necessary to estimate the size and time of formation of the heat flow distribution zone in the soil. It is advisable to study the regularities of the formation of the area of the thermal field around the working heat exchanger using mathematical modeling of the thermo-hydrodynamic processes of liquid filtration in a porous medium. Laboratory studies will not be able to give a real picture of the hydrodynamic process due to the need to observe the conditions of geometric and thermo-hydrodynamic similarity at the same time. Field studies do not allow to get a general picture of the process.

2. LITERATURE REVIEW

The construction of underground heat pumps is accompanied by the formation of thermal energy accumulation zones in the soil environment, which are characterized by a stable temperature deviation from the natural geothermal gradient (Gao, Zhang, & Xiao, 2020, Javadi, at all, 2019). In the context of the study of thermal effects on the soil environment, it is important to distinguish between two interconnected components of geothermal systems: underground heat exchangers and heat pumps. Heat exchangers are a system of pipelines buried in the soil, through which the coolant circulates and direct heat exchange with the geoenvironmental takes place – these elements are the source of the formation of the thermal area and the creation of zones of increased temperature in the soil.

Heat pumps, on the other hand, are located on the surface and are technological equipment that ensures the circulation of the heat carrier and the transformation

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of thermal energy obtained from the soil for the needs of heating or cooling the premises. Thus, from an environmental point of view, primary attention should be paid to underground heat exchangers as a direct source of heat load on the soil environment, while heat pumps determine the intensity and modes of this impact (Noorollahi, Y., & Peyvandi, 2025, Alkrush et all, 2025).

Thermal pollution of the environment is characterized by the formation of technogenic geofields of elevated temperatures as a result of industrial activity (Hrytsuliak, H., Marych, V., & Lynnyk, D, 2025). The thermal state of the soil regulates both soil-forming and biogeochemical processes: it controls water uptake by plants, their development, decomposition of organic matter, and hydrological dynamics – including the regime of snowmelt as the main source of river nutrition (Malek, K., Malek, K., & Khanmohammadi, F., 2021).

Therefore, even a slight change in the temperature regime of the soil and groundwater within a few degrees initiates a cascade of interrelated ecological disturbances: an imbalance in the biological activity of soil microorganisms, activation of the processes of dissolution and migration of heavy metal compounds in pore waters, disruption of the geochemical balance – in particular, a change in the concentration of dissolved oxygen and CO_2 (Parul et all, 2025). Groundwater in the zone of thermal influence also undergoes significant physico-chemical changes: the solubility of oxygen decreases, the corrosive activity of water increases, and the leaching of mineral components from water-bearing rocks intensifies (Sun at all, 2020).

The regularities of the distribution of fluids in a porous medium and the formation of the habitat were considered in the works of Grudz V.Ya. [1, 2], Mandrika O.M. [3], Zhdeka A.Ya. [4].

In the literature, two main models of heat dissipation are considered, which lead to various schemes of the formation of the thermal field. The processes of filtration of incompressible liquid in a porous medium can be considered analogous to the process of formation of the temperature field in the soil, since the mathematical models of thermal conductivity, hydrodynamics and diffusion are identical (Cui at all, 2024, Chen at all, 2025).

The first model considers the inequality of local convective flow velocities in a porous medium as the cause of scattering. The general essence of the model boils down to the fact that when a substance with an increased and constant concentration in time enters the flow along its entire cross-section, then at an arbitrary distance from the coordinate of the flow in time, the concentration of the substance in the flow will change from the initial value to the natural value characteristic of the flow of groundwater. This model leads to a scheme of piston displacement of natural waters by leaks from a constantly operating source.

The second model considers the branching and merging of elementary streams of liquid as they flow around the rock grains as the cause of scattering. The essence of the model boils down to the fact that when a substance with a given concentration is supplied from a fixed permanent source, which has significantly smaller geometric dimensions compared to the filtration area, the streams branch, which leads to an increase in the live cross-section of the flow and a decrease in the concentration of the substance. In this regard, a mixing zone is formed near the source, which has the appearance of an area, within which dispersion occurs with a decrease in the concentration of the substance as it moves away from the source. Thus, scattering does not occur from the moving filtering front, but relative to the source with fixed coordinates.

Considering both models, the researchers set the task of determining the concentration of the substance in the groundwater flow as a result of the dispersion of harmful leaks, while neglecting the study of the primary source of the formation of dispersion areas: the patterns of fluid filtration in a porous medium, which leads to their formation.

Setting the problem. The purpose of the research is to study the patterns of heat distribution in the porous medium during the formation of the thermal field area in the soil for environmental risk assessment.

The realization of the set goal comes down to solving the following research problems:

1. Assessment of the degree of lowering of the temperature of the energy carrier due to the contact of the heat exchanger with the ground.
2. Determination of the term for establishing thermal equilibrium between the heat exchanger and the soil.

3. RESULTS AND DISCUSSION

The source of the heat flow is the surface area of the heat exchanger, which is modelled by a set of parallel lines located in the same plane with a certain step. A non-stationary spatial problem is considered in the medium of normal cross-section and the region of formation of the area of the thermal field, in which the sources of heat flow are considered to be point sources. The physical picture of the process of heat propagation in a porous medium from a set of point sources is presented in the form of a superposition of the effects from each of the point sources. Therefore, at the initial stage, a mathematical model of heat propagation in a porous medium from one point source is considered. The environment is considered a homogeneous porous medium in which there is no heat flow.

When creating a mathematical model of the formation of the area of the thermal field, the following assumptions were made:

- the intensity of the heat flow from the walls of the heat exchanger is constant in time and is known;
- thermophysical characteristics of the steel soil during the process.

The basis of the mathematical model is the equation of non-stationary thermal conductivity in a porous medium [1]

$$\frac{\partial T}{\partial t} = æ\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)-\frac{q_V}{C_V\rho} \quad (1)$$

where: $T = T(x, y, z, t)$ – temperature as a function of time t and spatial Cartesian coordinates x, y, and z.

$æ=\frac{\lambda}{C_V\rho}$ – isochoric thermal conductivity of the medium, m²/c: λ – thermal conductivity, W/(mK); C_V – isochoric heat capacity, J/(kgK); ρ – density, kg/m³; q_V –

specific power of internal sources, W/m^3.

Due to the homogeneity of the medium (soil), the nature of heat propagation in all horizontal directions is considered identical, therefore, from the three-dimensional mathematical model (1) it is possible to move to a flat problem with horizontal coordinate x and vertical coordinate y. Point heat sources placed on the vertical cylindrical surface of the heat exchanger are modelled using the Dirac source function [4]

$$\delta(x-D/2)(y-h_0)=\begin{cases}0, & \text{of } x\neq D/2,\ y\neq h_0\\ \infty, & \text{of } x=D/2,\ y=h_0\end{cases}$$

where: D, h_0 – the outer diameter and height of the cylindrical surface of the heat exchanger.

Under these conditions, the non-stationary process of heat propagation in the vertical plane of the porous medium, caused by the action of a source of constant intensity, is considered. The problem is reduced to an inhomogeneous equation

$$\frac{\partial T}{\partial t}=æ\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}\right)-aT_H\delta\left(x-D/2\right)\left(y-h_0\right) \quad (2)$$

where $a=\frac{æ}{\pi D h_0}$; T_H - heat exchanger surface temperature.

The initial condition expresses the stability of the temperature in the porous medium before the influence of the heat exchanger, i.e. If the temperature reading is taken from its stable value in the undisturbed thermal state of the system, then the initial condition

$$T\left(x,y,0\right)=0 \quad (3)$$

The boundary condition on the surface of the heat exchanger expresses the exchange of heat with a liquid between the surface and the soil according to a linear law, i.e.

$$\left.\frac{\partial T}{\partial y}\right|_{y=0}=hT\left(x,0,t\right) \quad (4)$$

where h - is the proportionality factor.

The problem is solved using integral transformations. We apply the Fourier transformation to the variable

$$F\left(p\right)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}f\left(x\right)e^{-ipx}dx\,.$$

For time, t applies the Laplace transform

$$\bar{F}\left(s\right)=\int_0^{\infty}F\left(\tau\right)e^{-s\tau}d\tau\,.$$

At the same time, we will have

$$\frac{d^2 w}{dy^2}-\left(\frac{S}{æ}+p^2\right)\bar{\bar{w}}=-\frac{a}{\lambda\sqrt{2\pi}\,S}\delta\left(y-h_0\right)e^{-ip\left(\lambda+\frac{lD}{2}\right)} \quad (5)$$

$$\left.\left(\frac{d\bar{\bar{w}}}{dy}-h\bar{\bar{w}}\right)\right|_{y=0}=0\,. \quad (6)$$

Problem (5), (6) is solved by the method of variation of arbitrary variables

$$\bar{\bar{w}}=\frac{ae^{-\frac{ipD}{2}}}{2\sqrt{2\pi}S\sqrt{\frac{S}{æ}+p^2}}\left[S\left(y-h_0\right)e^{-\sqrt{\frac{S}{æ}+p^2}\,(y-h_0)}+\left(1-S\left(y-h_0\right)\right)e^{\sqrt{\frac{S}{æ}+p^2}\,(y-h_0)}\right]+\frac{ae^{-\frac{ipl_0}{2}}}{2\sqrt{2\pi}S\left(h+\sqrt{\frac{S}{æ}+p^2}\right)}\left(1-\frac{h}{\sqrt{\frac{S}{æ}+p^2}}\right)e^{-\sqrt{\frac{S}{æ}+p^2}\,(h_0+y)} \quad (7)$$

We find the inverse Laplace transform of the function (7).

$$\bar{w}(p,y,\tau)=\frac{ae^{-\frac{ipD}{2}}S(y-h_o)}{2\sqrt{2\pi p}}\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]+\frac{ae^{-\frac{ipD}{2}}}{4\sqrt{2\pi}\lambda p}\times$$
$$\times\left[e^{-p(h_o-y)}erfc\left(\frac{h_o-y}{2\sqrt{æt}}-p\sqrt{æt}\right)-e^{+(h_o-y)}erfc\left(\frac{h_o-y}{2\sqrt{æt}}+p\sqrt{æt}\right)\right]+\frac{ae^{-\frac{ipD}{2}}}{2\sqrt{2}\lambda}\times$$
$$\times\left[\frac{p-h}{2p(h+p)}e^{-p(h_o+y)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}-p\sqrt{æt}\right)+\frac{(p+h)e^{p(h_o+y)}}{2p(h-p)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+p\sqrt{æt}\right)-\right.$$
$$\left.-\frac{2he^{h(h_o+y)+ah^2\tau-ap^2\tau}}{h^2-p^2}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+h\sqrt{æt}\right)\right].$$

We find the inverse Fourier transform and get the solution to the problem (5), (6)

$$T(x,y,t)=\frac{aT_H}{4\pi}\int_{-\infty}^{\infty}\frac{e^{ipx}e^{-ip\frac{D}{2}}}{1}\left\{\frac{S(y-l_o)}{p}\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]+\frac{1}{2p}\times\right.$$

$$+\left[\frac{p-h}{2p(h+p)}e^{-p(h_o+y)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}-p\sqrt{at}\right)+\frac{(p+h)e^{p(h_o+y)}}{2p(h-p)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+p\sqrt{at}\right)-\right.$$
$$\left.\left.-\frac{2he^{h(h_o+y)+ah^2\tau-ap^2\tau}}{h^2-p^2}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+h\sqrt{at}\right)\right]\right\}dp.$$

This integral is reduced to the following form

$$T(x,y,t)=\frac{aT_H}{2\pi}\int_o^\infty\left(\cos px\cos p\frac{D}{2}+\sin px\sin p\frac{D}{2}\right)\left\{\frac{S(y-l_o)}{p}\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]+\right.$$
$$+\frac{1}{2p}\left[e^{-p(h_o-y)}erfc\left(\frac{h_o-y}{2\sqrt{æt}}-p\sqrt{at}\right)-e^{p(h_o-y)}erfc\left(\frac{h_o-y}{2\sqrt{æt}}+p\sqrt{at}\right)\right]+ \quad (8)$$
$$+\left[\frac{p-h}{2p(h+p)}e^{-p(h_o+y)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}-p\sqrt{at}\right)+\frac{(p+h)e^{p(h_o+y)}}{2p(h-p)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+p\sqrt{at}\right)-\right.$$
$$\left.\left.-\frac{2he^{h(h_o+y)+ah^2\tau-ap^2\tau}}{h^2-p^2}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+h\sqrt{at}\right)\right]\right\}dp.$$

If the vertical axis is moved from the axis of the cylindrical surface of the heat exchanger to its outer surface, then the heat source will be located on the axis $Y\left(\frac{D}{2}=0\right)$, so

$$T(x,y,t)=\frac{aT_H}{2\pi}\int_o^\infty\cos px\left\{\frac{S(y-h_o)}{p}\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]+\frac{1}{2p}\left[e^{-p(y-h_o)}\times\right.\right.$$
$$\times erfc\left(\frac{h_o-y}{2\sqrt{æt}}-p\sqrt{at}\right)-e^{-p(h_o-y)}erfc\left(\frac{h_o-y}{2\sqrt{æt}}+p\sqrt{at}\right)\Bigg]+ \quad (9)$$
$$+\left[\frac{p-h}{2p(h+p)}e^{-p(h_o+y)}erfc\left(\frac{h_o+y}{2\sqrt{æt}}-p\sqrt{at}\right)+\frac{(p+h)e^{p(h_o+y)}}{2p(h-p)}\times\right.$$
$$\left.\left.\times erfc\left(\frac{h_o+y}{2\sqrt{æt}}+p\sqrt{at}\right)-\frac{2he^{h(h_o+y)+ah^2\tau-ap^2\tau}}{h^2-p^2}erfc\left(\frac{h_o+y}{2\sqrt{æt}}+h\sqrt{at}\right)\right]\right\}dp.$$

For the stationary case, we obtain from (8).

$$T(x,y)=\frac{aT_H}{2\pi}\int_o^\infty\frac{1}{P}\left(\cos px\cos p\frac{D}{2}+\sin px\sin p\frac{D}{2}\right)\left\{\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]\times\right.$$
$$\left.\times S\left(y-h_o\right)+e^{-p(h_o-y)}+\frac{p\text{-}h}{p+h}e^{-p(h_o+y)}\right\}dp. \quad (10)$$

If the source is on the axis, $y\left(\frac{D}{2}=0\right)$, then we get

$$T(x,y)=\frac{aT_H}{2\pi}\int_o^\infty\frac{\cos px}{p}\left\{\left[e^{-p(y-h_o)}-e^{p(y-h_o)}\right]S\left(y-h_o\right)+e^{-p(y-h_o)}+\frac{p\text{-}h}{p+h}e^{-p(h_o+y)}\right\}dp \quad (11)$$

To obtain numerical solutions and their analysis, we will use the concept of dimensionless time

$$\tau=\frac{æt}{\pi Dh_0} \quad (12)$$

For the conditions of the experiment, the thermal conductivity of the soil was $\lambda = 1{,}9$ W/mK, isochoric heat capacity $C_V = 1072$ J/kgK, density $\rho = 1{,}4$ g/m³. So

$$æ=\frac{\lambda}{C_V\rho}=\frac{1{,}9}{1072*1400}=1{,}27*10^{-6}\ \text{m}^2/\text{c}$$

The time span of one day (86400 s) corresponds to dimensionless time

$$\tau=\frac{æt}{F}=1{,}27*10^{-6}86400/31{,}42=3{,}5*10^{-3}$$

where $F = \pi Dh0 = 31{,}42$ m² – the area of the side surface of the heat exchanger.

Under the specified conditions, on the basis of solution (9), graphical dependences of the environmental temperature change with depth were constructed for different distances from the heat exchanger wall and different values of dimensionless time in the process of the formation of the temperature field in the soil, which are shown in Fig. 1. The analysis of the results of the simulation of the process of the formation of the thermal field in the soil shows that at the initial moments of time there is an intensive heat transfer from the heat exchanger wall to the environment, and with the passage of time this intensity is decreasing So, for a period of time $\tau = 0{,}0035$ (approximately one day), the maximum temperature at a distance of 1 m from the wall of the heat exchanger will increase by 14.5 K, and the distribution along the depth will be uneven: from 11 K at a depth of 1 m to 14.5 K at a depth of 4 m. The uneven distribution of temperatures along the depth is explained by the principle of building a mathematical model, which assumes that the temperature on the soil surface is constant. At a distance of 4 m, the maximum temperature increase will be 6.5 K, and at a distance of 5 m-1b5 K. At a distance of 10 m from the wall of the heat exchanger, the temperature increase is practically not felt.

For a period of time $\tau = 0{,}01$ (about three days), the increase in the maximum temperature at a distance of 1 m from the wall of the heat exchanger will be 14.6 K, that is, in this section, the temperature over three days can be considered stationary. At a distance of 4 m, the maximum increase in temperature will be 11.6 K, i.e., in this section, the formation of the area of the temperature field continues, as in more distant sections: at a distance of 10 m, the temperature increase will be 6.4 K, at a distance of 20 m-3.1 K, at a distance of 30 m-1.2 K. At a distance of 40 m, the temperature regime remains practically unchanged.

For a period of time $\tau = 0{,}0175$ (about four and a half days), the increase in the maximum temperature at a distance of 1 m from the wall of the heat exchanger will be 14.61 K, that is, a stationary temperature regime is observed. Similar temperature indicators are observed at distances of 2-5 m, which indicates a formed temperature range. At greater distances, the formation of the temperature field continues, for example, at a distance of 10 m, the temperature rise will be 11.6 K, at a distance of 20 m - 10.7 K, at a distance of 30 m - 4.8 K, at a distance of 50 m - 1.3 K. Calculations show that the formation of the area of the temperature field practically ends in $\tau = 0{,}0192$ (five and a half days).

To evaluate the energy efficiency of the heat exchanger, we will use the concept of efficiency (efficiency), which is determined by the ratio

$$\eta = \frac{Q_+ - Q_-}{Q_+} \tag{13}$$

where Q_+, Q_- – respectively, the amount of added and removed (lost) heat.

The heat supplied with water during the formation of the area of the temperature field t_f at its temperature at the entrance $T_н$ with flow rate q will be

$$Q_+ = q\rho t_f C_v^B T_H \tag{14}$$

Heat losses in the soil during the same time will add up

$$Q_- = V\rho t_f C_v^G \, \Delta T \tag{15}$$

where C_v^B, C_v^G – specific isochoric heat capacities of water and soil; ΔT – heat difference between the temperatures of the energy carrier (water) and the environment (soil).

$$\Delta T = T(x, y, t_f) - T_0$$

Based on (15) and (9), we obtain

$$Q_- = \pi\rho C_v \int_{D/2}^{R} \int_{0}^{h_0} T(x, y, t_f)\, dxdy$$

where R - the radius of the contour of the area of the thermal field.

Calculations show that when supplying an energy carrier with a consumption of 40 m^3/h. With a temperature of 150C, the heat of the heater will be 3.3216 GJ, and the heat of the refrigerator (heat loss) will be 0.56 GJ, with such indicators, the efficiency of the system will be $\eta = 0{,}8314$. From another approach, the estimated temperature of the energy carrier after the heat exchanger will be 12.5 °C.

The calculated efficiency factor of the system $\eta = 0.83$ indicates that about 17 % of the total thermal power is irreversibly dissipated into the surrounding soil environment. With a system power of 3.3 GJ, this means that 0.56 GJ of thermal energy enters the geoenvironment – the amount sufficient to change the temperature of about 300 m^3 of soil by 5°C. Such an energy load on the underground ecosystem is significant and needs to be taken into account during the environmental examination of projects that involve the use of underground heat exchangers. The obtained modelling results allow ecological zoning of the territory around the underground heat exchanger depending on the degree of thermal influence.

The zone within a radius of 0-4 m from the wall of the heat exchanger should be classified as acute thermal pollution, where the thermal balance of the soil environment is disturbed. The area at a distance of 4-20 m is characterized as a zone of moderate thermal influence, where a steady increase in temperature is observed, which can potentially lead to long-term changes in the structure of soil communities of microorganisms and disruption of the processes of biogeochemical cycling of elements. Beyond 20 m, a buffer zone is formed, where temperature changes do not exceed natural fluctuations, but require environmental monitoring to detect possible cumulative effects.

At the initial stage of system operation, the efficiency has a maximum value, but due to the accumulation of heat losses in the soil environment, it gradually decreases and stabilizes after the formation of the temperature range.

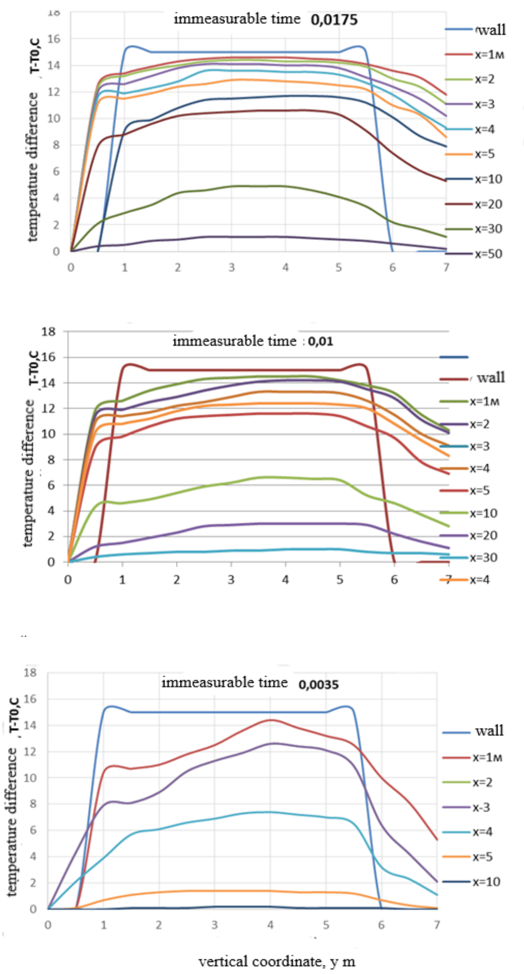

Fig. 1 – The formation of the temperature field in the soil during the operation of the heat exchanger depending on spatial coordinates and time

The colour map shows the increase in soil temperature ΔT, obtained on the basis of mathematical modelling of the heat transfer process. The dashed circles mark the boundaries of the zones of thermal influence: the zone of acute thermal pollution (0-4 m) and the zone of moderate thermal influence (4-20 m). The central point corresponds to the position of the underground heat exchanger.

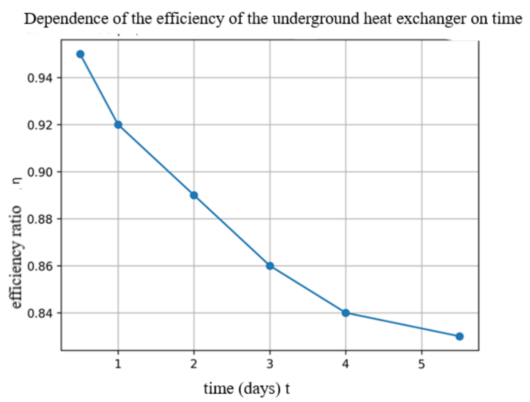

Fig. 2 – Dependence of the efficiency of the underground heat exchanger on the time of operation

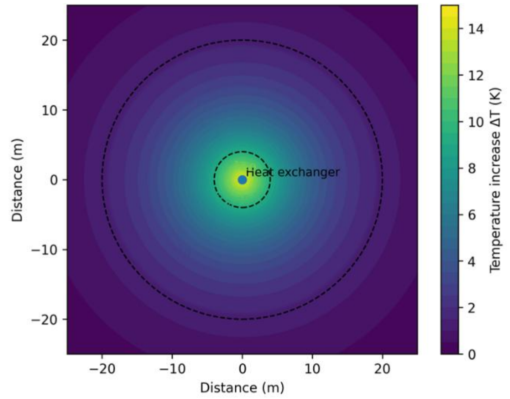

Fig. 3 – Spatial distribution of the temperature field in the soil environment around the underground heat exchanger (2D isotherm map)

The analysis of the dynamics of the formation of the thermal area shows that the greatest environmental risk occurs during the first 5.5 days of operation of the heat exchanger, when there is a rapid accumulation of thermal energy in the soil environment. During this period, the temperature field reaches a stationary state, which means the formation of a stable centre of thermal pollution. It is important that even after the heat exchanger is stopped, the thermal area is preserved for a long time due to the low thermal conductivity of the soil, which can potentially lead to the accumulation of negative environmental effects during periodic or cyclical operation of the equipment. To reduce the negative environmental impact of underground heat exchangers, it is recommended to maintain a minimum sanitary and protective distance of 25-30 m from groundwater intakes and environmentally sensitive objects. It is mandatory to implement a system of thermometric monitoring of groundwater in the affected area with periodicity at least once a quarter. For newly built facilities, it is advisable to apply thermal insulation of the underground sections of the heat exchanger and optimize the operating modes in order to reduce peak heat loads on the geoenvironmental.

4. CONCLUSIONS

1. A mathematical model of the non-stationary process of thermal energy propagation in two-dimensional space has been created and methods of its implementation have been proposed, which ultimately makes it possible to find an analytical solution to the given problem and to establish, on its basis, the general regularities of the formation of the temperature range in a porous medium (soil) for given characteristics of the energy carrier and the environment.

2. Numerical realizations of the problem for different conditions allow to establish the degree of dissipation of heat energy in the soil, which is estimated by the useful coefficient of the system, and to establish the duration of the process of formation of the thermal area.

3. It was established that the operation of underground heat exchangers leads to the formation of a stable zone of thermal pollution with a radius of up to 20–30 m, which creates an ecological risk for underground water and soil ecosystems.

4. The calculated efficiency factor of the system

$\eta = 0.83$ means that 17% of thermal energy (0.56 GJ) irreversibly enters the geoenvironmental, creating a significant environmental burden on the underground ecosystem, which requires mandatory consideration during the environmental examination of such projects.

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Регламент формування зони теплового впливу підземного теплообмінника як фактора екологічного ризику для ґрунтового середовища

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Розглянуто задачу встановлення закономірностей створення теплової області в ґрунті при використанні теплообмінників вторинних джерел енергії. Характеристики нестаціонарного процесу поширення теплової енергії в ґрунті та пов'язана з цим інформація про ступінь охолодження енергоносія в процесі формування температурного діапазону та тривалість процесу є важливими питаннями, що розглядаються в процесі реалізації задачі. Вивчення цих закономірностей дозволяє оцінити не тільки енергетичну ефективність використання вторинних джерел енергії, але й їх екологічну безпеку для підземного середовища. Аналітичний підхід до вирішення задачі вимагає створення математичної моделі та методології її реалізації. Запропоновано математичну модель, яка базується на диференціальному рівнянні нестаціонарної теплопровідності у двовимірній постановці та доповнена початковими та граничними умовами, що характеризують реальний процес формування теплової області. Реалізація математичної моделі здійснювалася методом використання інтегральних перетворень, зокрема, застосовувалися перетворення Лапасса та Фур'є. В результаті було отримано аналітичне рішення, яке дозволило оцінити характерні закономірності процесу. Для отримання числових рішень та їх аналізу скористаємося концепцією безрозмірного часу. Чисельна реалізація задачі для різних умов дозволяє встановити ступінь дисипації теплової енергії в ґрунті, який оцінюється коефіцієнтом корисної дії системи, та встановити тривалість процесу формування теплової області.

Ключові слова: Теплове забруднення, Теплообмін, Математична модель, Термічна деградація ґрунту, Термічна зона, Екологічний ризик, Підземні води.