Ground moisture phase transitions:
Accounting in BHE'S design

Фазовые переходы влаги в грунте:
Учет при проектировании грунтовых теплообменников

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Abstract. The results of numerical and experimental studies devoted to the evaluation of the effect of phase transitions of pore moisture in the soil mass surrounding the borehole heat exchangers (BHE) on the thermal conductivity of the adjacent soil and on the temperature of the coolant circulating through the heat exchanger are presented. A mathematical model is presented that allows one to describe the spatial non-stationary thermal regime of a soil massif with BHEs, taking into account the processes associated with phase transitions of moisture in the pore space of the soil. This mathematical model is based on the method of accounting the latent heat of phase transitions of pore moisture in the ground by the use of such a parameter as the "equivalent" thermal conductivity. The essence of the method is to take into account the heat of phase transitions of pore moisture in the ground by introducing a new "equivalent" thermal conductivity of the soil, consisting of the direct thermal conductivity of the soil and an additive that is responsible for the freezing / thawing of pore moisture. The methods, equipment and results of experimental studies on the «equivalent» thermal conductivity of soil accounting the phase transition of pore moisture during freezing and thawing performed in laboratory on the test bench simulating borehole heat exchangers working conditions are described. The results of the simulation illustrate the need to take into account the phase transitions of the ground moisture in the ground during the design of BHEs. The effect caused by pore moisture condensation during the operation of BHEs and the associated intensification of the processes of heat exchange was experimentally observed.

Аннотация. В статье приведены результаты численных и экспериментальных исследований, посвящённых оценке влияния фазовых переходов поровой влаги в грунтовом массиве, окружающем термоскважины, на теплопроводность прилегающего грунта и на температуру теплоносителя, циркулирующего через теплообменник. Представлена математическая модель, позволяющая описать пространственный нестационарный тепловой режим грунтового массива с термоскважинами с учётом процессов, связанных с фазовыми превращениями влаги в поровом пространстве грунта. Данная математическая модель основывается на методе учёта скрытой теплоты фазовых переходов поровой влаги в грунте за счёт использования такого параметра, как «эквивалентная» теплопроводность. Суть метода состоит в том, чтобы учесть теплоту фазовых переходов поровой влаги в грунте с помощью введения новой «эквивалентной» теплопроводности грунта, состоящей из непосредственно теплопроводности грунта и добавки, учитывающей замерзание/оттаивание поровой влаги.

Описаны методы, оборудование и результаты экспериментальных исследований по оценке «эквивалентной» теплопроводности грунта, учитывающей фазовый переход поровой влаги при замораживании и оттаивании грунта, выполненные в лабораторных условиях на экспериментальном стенде, моделирующем эксплуатационные режимы термоскважин. Результатами моделирования проиллюстрирована необходимость учёта фазовых переходов поровой влаги в грунте при проектировании ГТСТ. Экспериментально обнаружен эффект, вызываемый конденсацией при эксплуатации ГТСТ водяного пара, содержащегося в поровом пространстве грунта, и связанная с этим интенсификация процессов теплообмена между термоскважиной и грунтом.

Introduction

Currently, the use of geothermal heat pumps (GSHP) is quite a popular solution for providing heating, hot water supply and conditioning in buildings of various purposes due to their energy efficiency and environmental friendliness [1–3]. These systems are actively used including in regions with a cold climate [4–7].

One of the most important parts of such systems are the borehole heat exchangers (BHE) which are used for extraction/rejection heat from the ground and in most cases determine the whole systems efficiency.

The two most commonly used modifications of BHEs are coaxial and U-shaped.

Coaxial BHEs represent a large diameter pipe, inside which a smaller diameter pipe is located so that the coolant supplied through the inside pipe is then introduced into the annular channel, raising there and exchanging heat with the surrounding ground through the wall of the larger (outside) tube. Coaxial BHEs can be made of both metal and polyethylene, where the inner tube is usually made of polyethylene as a material with a lower thermal conductivity in order to minimize the thermal interference of descending and ascending flows of coolant (thermal short circuit effect).U-shaped models are mainly made of plastic tubes and used in two modifications - with one or two U-shaped loops within a single borehole.

BHEs functioning in cold regions have to meet some additional challenges. The heating period in most of Russia's territory is noticeably longer and the ambient temperatures are much lower than, for example in Europe, all this leads to a significant decrease in ground temperatures during the operation of the GSHP, which in turn leads to a decrease in their efficiency.

There are several ways to cope with this effect: increasing borehole space [8, 9], modifying borehole layout [10], improving thermal properties [11], but the most common way is to increase the length or the number of the ground heat exchangers [12].

At present, many works are being devoted to the search for ways to improve the efficiency of ground heat exchangers, and part of them are aimed at studying the thermal conductivity: the effect of both the thermal conductivity of the materials used in the heat exchanger [13–15] and the thermal conductivity of the soil surrounding BHEs [16, 17].

The long-term operation of GSHP in the climatic conditions of most Russia's territory causes freezing and thawing of the soil surrounding the borehole heat exchanger [18, 19]. Accounting for these processes within mathematical models of such complicated multi-component pore structures as soil is an extremely difficult task [20].

In a precise approach, in the design of borehole heat exchangers not only ground moisture phase transition mechanisms and heat and mass transfer processes, but also chemical and mineralogical composition of soil, mechanical structure of hard particles material, the degree of dispersion in the medium, shape and size of both particles and pores, the ratio of different water phases and their distribution across the soil, and lots of other physical and chemical parameters of soil massif should be accounted for. A detailed account of these factors with the help of a modern mathematical apparatus, as demonstrated by the study of existing heat transfer models of the soil-BHE system [21–24], is practically impossible. But on the other hand we have to make a years-long forecast of how BHE will interact with ground during GSHP operation in order to guarantee system's reliability.

To make a quite accurate forecast and at the same time to simplify calculations, for the practical purposes in the GSHP design it is possible to describe all these multiple factors using the model of «equivalent» thermal conductivity developed by A.F.Chudnovsky [21] by the standard conductivity equation with "equivalent" heat and mass transfer parameters. In this case, the soil is considered as a

quasihomogeneous body, to which the usual heat conduction equation is applicable, and its thermal characteristics can vary both in time and in coordinates.

Special mention should be made of the need to take into account the influence of pore moisture and it's migration has on the thermal processes occurring during the operation of the GSHP. In the capillary-porous system, which is a soil massif, the presence of moisture in the pore space has a significant effect on the process of heat distribution. So, for example, if there is a temperature gradient in the ground massif, the water vapor molecules move to a zone having a lower temperature. But at the same time, under the action of gravitational forces, a directed flow of moisture in the liquid phase appears which can partially compensate for heat fluxes carried by vapor moisture and, consequently, reduce the influence of migration processes of moisture on the thermal performance of BHE. Correct accounting of such influence for today is associated with considerable difficulties.

This research is devoted to developing of simple and accurate enough for practical purposes method of considering ground moisture freezing and thawing around the BHE during its operation. The objectives of research are to propose and adequate mathematical model, using an "effective" heat and mass transfer characteristics of soil to account for ground moisture phase transitions, and to evaluate «effective» thermal conductivity of soil in both heat rejection and heat extraction modes.

In this research, the problem of developing a mathematical model allowing one to describe in simple form the heat transfer process in a two-phase medium with an unknown position of the phase boundary (Stefan's problem) was solved, as well as the problems of estimating the effect of phase transitions of the ground moisture in the soil on its "equivalent" heat conductivity and on the overall efficiency of the geothermal heat pump system.

Research methods

Numerical study

The non-stationary process of heat transfer, including taking into account the humidity of the medium, is considered in [25–27].

The mathematical model represented here is based on a simplified description of the spatial non-stationary thermal regime of the cylindrical soil massif in which the BHEs are located.

The heat conduction equation for this case in cylindrical coordinates is as follows [28]:

$$c\rho\frac{\partial t}{\partial \tau} = \lambda_g \left(\frac{\partial^2 t}{\partial r^2} + \frac{1}{r}\frac{\partial t}{\partial r} + \frac{\partial^2 t}{\partial z^2} \right), \tag{1}$$

where τ – is time, hours;

r – radius of the cylinder under consideration, m;

z – vertical coordinate, m;

T(r,z,τ) - deviation of soil temperature from natural values, °C;

c – specific heat of the soil, J/(kg×°C);

ρ – soil density, kg/m³;

λ_g – thermal conductivity of the soil, J/(h×m×°C);

It is important to note that equation (1) does not take into account the latent heat of phase transitions; therefore, it is applicable only if the ground temperature remains positive during the operation of the heat pump. In actual fact, during the operation of the GSHP the temperature of the soil near the borehole heat exchangers can drop below zero. In this case, the moisture contained in the soil will freeze, releasing the latent heat of the phase transition of water from the liquid state to the solid state. After heat collection is terminated (e.g. in summer) the frozen moisture will thaw, i.e. there will be a reverse phase transition that absorbs additional heat energy from the soil.

Thus, instead of equation (1) the Stefan problem should be solved – the problem concerning the heat transfer in a biphasic system with the unknown position of the phase boundary. The solution for the Stefan problem in this case may be obtained only numerically, besides because of the problem's non-

linear nature, these methods i=ought to be iterative. Moreover, solving the Stefan problem for a considerably long period (years) requires a lot of CPU time. And for the significant cost of computational resources used for obtaining an accurate solution in the design of GSHP as a rule are not justified. Therefore, at the design stage, it is advisable to use more cost-effective methods of taking into account the latent heat of phase transitions for the determination of soil temperature, one of which was developed by the authors of this paper and is presented below.

The essence of the method is to account for the heat of phase transition of ground moisture in the soil by introducing a new "equivalent" ground thermal conductivity λ_{eq} consisting of ground thermal conductivity itself and additives, taking into account the freezing / thawing of ground moisture.

During the freezing of the soil, the volumetric heat of the phase transition can be determined by the following equation [29]:

$$L_v = m\sigma\rho \tag{2}$$

where L_v – volumetric heat of phase transition, $W \cdot h/m^3$;

m – volumetric humidity of soil, (m^3 of moisture/m^3 of ground);

σ – phase transition heat of a unit of weight of water, equals 93 $W \cdot h/kg$ [29];

ρ – density of the solidification agent (ice), kg/m^3.

Consider the problem of freezing an unlimited body of soil with a cylindrical cavity (borehole heat exchanger tube), the design scheme of which is shown in

Figure 1, where the following notation is used:

R_k – boundary of soil freezing, m;
q_{st} – heat flow density (per 1 linear meter of cylinder) from the unfrozen soil, W/m;
t_p – temperature at the surface of the cylindrical cavity, °C;
t_0 – freezing temperature of water in the pores of the body of soil, $t_0 = 0$ °C;
t_r – the temperature of the soil infinitely distanced from the cylindrical cavity (borehole heat exchanger), °C;
R_0 – radius of the cylindrical cavity (the borehole heat exchanger), m.

The design scheme in fact illustrates the operating conditions of a borehole heat exchanger with radius R_0. Indeed, after a time τ (h) when the soil contacting with the heat exchanger tube reaches the temperature tp (°C), lower than $t_0 = 0$ °C, a region of frozen soil of radius R_k appears.

The heat balance equation for the soil freezing around the heat exchanger with radius $r = R_k$ in the absence of heat input from the unfrozen soil (($t_r \approx$ or slightly greater than t_0) is as follows.

$$q_t = q_{st} + q_{ft}, \tag{3}$$

where q_t – specific (per 1 meter of the tube) thermal flow to the heat exchanger tube, W/m;

q_{st} – specific heat flow from the unfrozen soil, W/m;

q_{ft} – specific heat flow, caused by the release of latent heat of ground moisture phase transition in the freezing soil, W/m.
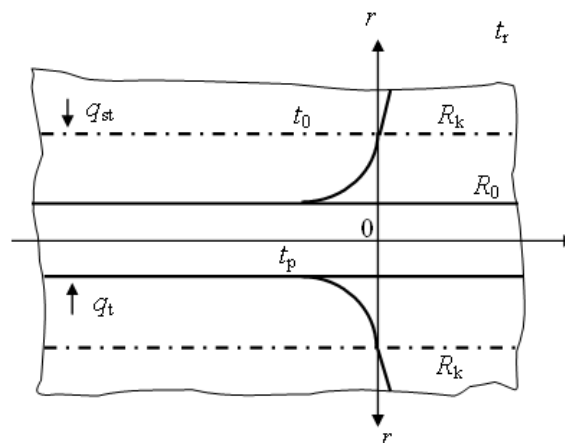

Figure 1. Design scheme for freezing an unlimited body of soil with a cylindrical cavity

Assume that all heat flows are conditionally constant and averaged over time. Then to determine them the following expressions can be used:

$$q_t = \frac{2\pi\lambda_{\text{экв}}}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right),$$

(4)

$$q_{st} = \frac{2\pi\lambda_g}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right)$$

(5)

$$q_{ft} = \pi\left(R_k^2 - R_0^2\right)\frac{L_v}{\tau}$$

(6)

where: λ_g – thermal conductivity of the frozen soil, W/(m·ºC);

$\lambda_{\text{экв}}$ - "equivalent" thermal conductivity of the soil, accounting for the release of the latent heat of ground moisture phase transition, W/(m·ºC);

τ - time needed for freezing of soil within the radius R_k, h.

Thus by introducing $\lambda_{\text{экв}}$ we substituted the problem of thermal conditions in a cylinder of frozen soil around the heat exchanger tube with radius R_k and thermal conductivity λ_g by a quasi-stationary problem (4) with similar temperature distribution, same boundary conditions (boundary temperatures are respectively t_0 and t_p), but with another "equivalent" thermal conductivity $\lambda_{\text{экв}}$, which accounts for pore moisture phase transitions.

An "equivalent" problem is the problem of the stationary thermal regime of an unlimited soil massif with a cylindrical cavity whose temperature field coincides with the temperature field of the main problem (with the region of the frozen ground of the Stefan problem), presented in Figure 1, but there is no latent heat released. Obviously, it is possible to achieve an approximately similar temperature distribution in both cases only by introducing new thermal conductivity of the soil to the second problem - $\lambda_{\text{экв}}$, that is in fact an "equivalent" thermal conductivity of the soil, that ensures that temperature distributions coincide, or at least are very similar to one another.

To determine q_{st} we use the same quasi-stationary problem (5), with the same boundary conditions, but with the actual thermal conductivity of the soil, W/(m·ºC).

To determine q_{ft} (6) lets average the amount of thermal energy released during the freezing of the hollow cylinder with an inner radius R_0 and outer radius R_k over time τ.

The other way to determine q_{ft} is to, as in expressions (4) and (5), use the same quasi-stationary problem (remember, that the heat flow from the unfrozen soil equals "0") with thermal conductivity λ_{ft}, that ensures thermal impact on the heat exchanger equivalent to (6). In this case, q_{ft} can be expressed as follows

$$q_{ft} = \frac{2\pi\lambda_{ft}}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right)$$

(7)

Thus by introducing expressions (4), (5) and (7) into equation (3), we may present the heat balance equation in a new form:

$$\frac{2\pi\lambda_{\text{экв}}}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right) = \frac{2\pi\lambda_g}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right) + \frac{2\pi\lambda_{ft}}{\ln\left(R_k/R_0\right)}\left(t_0 - t_p\right)$$

(8)

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Dividing both parts of the equation (8) by $\dfrac{2\pi}{\ln\left(R_k/R_0\right)}\left(t_0-t_p\right)$, produces a new expression for $\lambda_{\text{экв}}$

$$\lambda_{\text{экв}} = \lambda_g + \lambda_{ft}. \tag{9}$$

Finally, the "equivalent" thermal conductivity of ground, accounting for the latent heat of pore moisture phase transitions, equals to the actual ground thermal conductivity, increased by the "virtual" part λ_{ft}, which can be determined from the equality of expressions (6) and (7):

$$\frac{2\pi\lambda_{ft}}{\ln\left(R_k/R_0\right)}\left(t_0-t_p\right) = \pi\left(R_k^2 - R_0^2\right)\frac{L_v}{\tau}. \tag{10}$$

Solving the equation (10) for λ_{ft}, obtain the required expression

$$\lambda_{ft} = \frac{L_v\left(R_k^2 - R_0^2\right)}{2\tau\left(t_0-t_p\right)}\ln\left(R_k/R_0\right). \tag{11}$$

Thus, all the unknowns needed to calculate the "equivalent" thermal conductivity of the soil $\lambda_{\text{экв}}$, except for R_k have been determined.

To determine R_k consider the same quasi-stationary problem (the case when $q_{st} = 0$) and write down the heat balance equation at the boundary of soil freezing]

$$-\lambda_g\frac{t_0-t_p}{R_k\ln\left(R_k/R_0\right)} = L_v\frac{dR_k}{d\tau}. \tag{12}$$

The solution for this equation looks as follows:

$$\eta_k^2\left(2\ln\eta_k - 1\right) + 1 = 4\Pi. \tag{13}$$

where:

$$\eta_k = \frac{R_k}{R_0}; \quad \Pi = \frac{\lambda_g\tau\left(t_0-t_p\right)}{L_v R_0^2}. \tag{14}$$

The equation (13) may be solved numerically, using, for example, the Newton's method. The obtained value of R_k is used for calculating λ_{ft} from (11).

Experimental study

Experimental study of estimation of "equivalent" thermal conductivity of the ground, accounting for the phase transition of the ground moisture during the thawing and freezing of the soil, has been performed in the laboratory on the test bench simulating borehole heat exchangers working conditions. The scheme of the test bench is shown on Figure 2, and its photograph on Figure 3.

The test bench consisted of two models of borehole heat exchangers - metal tubes with the outer diameter of 33.5 mm, inner diameter of 27.1 mm and wall thickness of 3.2 mm. Metal-plastic pipes 15 mm in diameter were placed inside metal pipes, and the ends of the metal tubes were plugged. Heat-carrying medium was pumped into the borehole model through the inner pipes, and flowed out through the annulus. Water solution of ethylene glycol was used as heat-carrying medium. Models of boreholes were placed inside plastic finned tubes with internal diameter of 314 mm. The space between borehole model and the plastic tube is filled with soil. Borehole model No. 1 is placed in loam and borehole model No. 2 is placed in sand. The soil properties are shown in the Table 1 [30]. The length of each model is 2 m. The borehole models are parallel connected to the hydraulic circuit along with the refrigeration unit and the electric heater. Either the electric heater or the refrigeration unit are turned on depending on experiment's purpose - simulating of summer or winter conditions. The refrigeration unit was placed into

isolated chamber to avoid the influence of heat from its condensers on thermal conditions of the laboratory facilities and boreholes under study.

To measure the soil temperature, the soil temperature sensors of the TP101 series were used with the measurement error ± (0.15 ºC + 0.002 | T |), and the coolant temperature was measured by submersible Pt1000 sensors with a measurement error of 0.3ºC + 0.002 | T |, where T - current measured temperature.

The flow rate of the heat carrier was determined from the readings of the water meter with a measurement error of ± 2 %.

The measurements were carried out with a periodicity of 5 minutes.

The thermal load Nt, W, supplied to the BHE, was determined as

Nt = Cp * ΔT * G,

where Cp - is the specific heat of the coolant, J / (kg * °C);

ΔT - temperature difference at the inlet and outlet of the BHE;

G - coolant flow, kg / s.

Table 1. Thermal and physical properties pf the soil [30]

	Soil type	Density, kg/m³	Heat capacity when thawed, J / (kg * K)	Heat capacity when frozen, J / (kg * K)	Thermal conductivity when thawed, W / (m * K)	Thermal conductivity when frozen, W / (m * K)
Borehole 1	Clay loam	2000	2.26	2.10	1.16	1.27
Borehole 2	Sand	1800	2.42	2.04	1.97	2.20

Three series of experiments were conducted.

The purpose of the first series of experiments was to determine the «equivalent» thermal conductivity of the soil at heat extraction regime.

The procedure for conducting experiments in this series was as follows. The flow rate of the heating medium through Borehole 2 was overlapped in order to ensure that all cooling power was directed to Borehole 1. The refrigeration machine was switched on and ground temperatures were recorded. At the same time, the room temperature was maintained at +18 °C. The soil around the Borehole was frozen. The soil was humidified, and then kept at almost stationary humidity conditions. The electric power meter was measured using an electric meter, after which the «equivalent» thermal conductivity of the soil was determined.

The purpose of the second series of the experiments was to determine the «equivalent» thermal conductivity of the soil at heat rejection regime.

The procedure for conducting experiments in this series was as follows. The water heater was turned on, equal coolant flow rates for both boreholes were set, and the parameters of the soil temperature and humidity were recorded. At the same time, the room temperature was maintained at 20 °C. After the heater was turned off, the soil was moistened, brought to the stationary humidity regime, after which the heater was switched on again. By electric meter, the electric power consumption was measured, and then the «equivalent» thermal conductivity of the soil was determined.

The purpose of the third series of the experiments was to evaluate the impact of cyclical loads and heat-accumulating properties of the soil on its "equivalent" thermal conductivity.

The experiments of this series included three periods: the first period - heat extraction - the chiller was switched on, the second period - the heat rejection - the electric heater was turned on, and the chiller was switched off, and the third period - heat extraction - the electric heater was switched off and the chiller was switched on again. At the same time, the temperature of the indoor air in the laboratory room was maintained at a constant level. The electric meter measured the consumed electric power, the specific heat exchange was determined for 1 m of the length of the boreholes, and then the "equivalent" thermal conductivities of the soil were determined for each period.
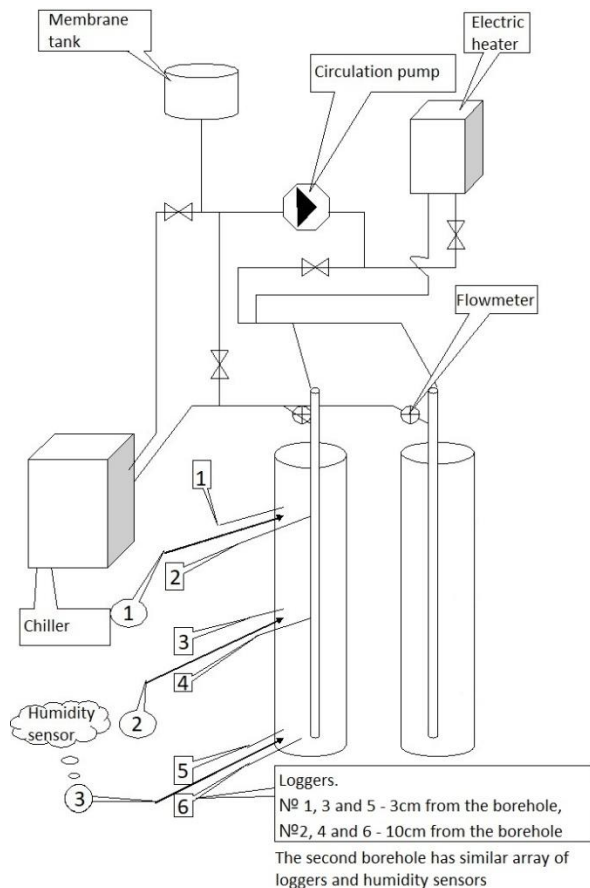
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Figure 2. Test bench schematics

Figure 3. Photo of borehole models

Results and discussion

Numerical study

Numerical studies were carried out using the mathematical model described above. To implement it, a computer program was created.

Calculations were carried out using the example of a hypothetical cottage with a heated area of 200 square meters, equipped with GSHP with a single vertical borehole of 0.16 m in diameter and 70 m in depth. Climatic conditions were taken for the city of Moscow. Ground considered was a loam with a volume weight of 2000 kg / m³ with a thermal conductivity of 1.16 W / (m * °C). The natural undisturbed temperature of the ground is 8 °C. GSHP provides only the heating, without domestic hot water. The beginning of the countdown is the beginning of the heating season - October 1. The time horizon for modeling is the first 60 months of system's operation.

When performing calculations, the influence of the process of pore moisture freezing was evaluated. Two options were calculated - without taking into account the freezing and with its account. As the evaluation criterion, the temperatures of the coolant and the ground at the entrance to the borehole were assumed (the minimum temperature, after the heat pump evaporator).

Figure 4 shows the graphs of the temperature change of the heat carrier of borehole during operation, calculated without taking into account and taking into account the freezing of pore moisture.

Figure 5 shows graphs of the change in the freezing radius of the soil around the borehole during its operation, as well as the "equivalent" thermal conductivity of the soil, determined according to the methodology described in paragraph 2.1. of this article.
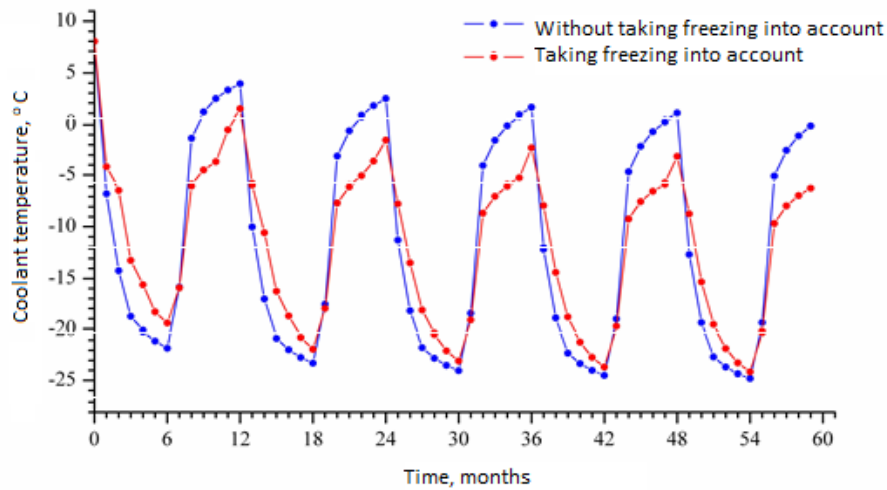
Figure 4 Temperature of the coolant in a borehole heat exchanger, calculated with and without taking into account freezing of ground moisture in the body of soil
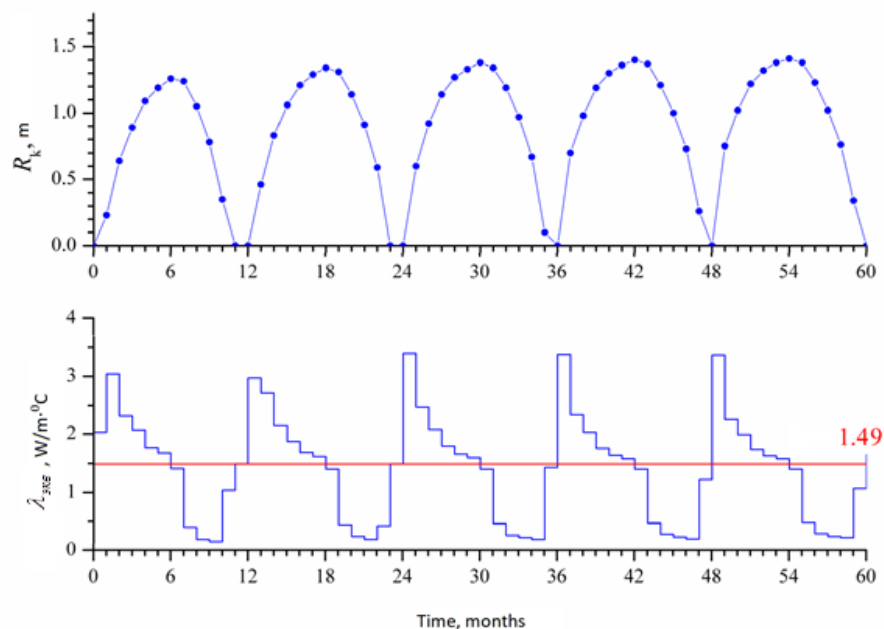

Figure 5. Radius of frozen soil around the borehole heat exchanger and «equivalent» thermal conductivity of the soil

As can be seen from the graphs presented in Figure 4, that taking into account the freezing of pore moisture the coolant temperature by the end of the heating period (the minimum points in the graph of Figure 4) is higher by 3 °C in the first year of operation than in the calculation without taking the freezing into account, but in following years this temperature difference decreases.

The maximum temperature of the coolant in the case of freezing is below the analogous temperature for the case when phase transitions of pore moisture are not taken into account.

The upper graph in Fig. 5 shows that in the operating conditions under consideration, an ice formed around the borehole during its work, has enough time to defrost in first two years, but on the third and subsequent periods complete melting of ice does not occur.

The «equivalent» thermal conductivity of the soil (the lower graph in Fig. 5.), taking into account the latent heat of freezing of the pore moisture, varies from 1.16 to 3.0 W / (m * ° C) during the heating period, and the average for the first five heating periods "equivalent" thermal conductivity is 1.49 W / (m * °C).

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Experimental study

The results of all three series of experiments are shown in table 2. The data in Table 2 are obtained by averaging the corresponding parameters during the test period (indicated in the second column). Average for a period of specific heat extraction from 1 m of the BHE was calculated by dividing the average heat load per BHE by its length.

Table 2. The results of the three series of experiments

№	TEST PERIODS	Average heat extraction from 1 meter of BHE during the period q_{st}, W/m	Average coolant temperature, °C	Average soil temperature 50 mm away from the BHE, °C	Average soil temperature 100 mm away from the BHE, °C	Average "equivalent" thermal conductivity of the soil Rk=50, W/(m°C)	Average "equivalent" thermal conductivity of the soil Rk=100, W/(m°C)
First series (heat extraction)							
BHE №1 (clay loam)	No. 1 (77 h)	291	-13.9	-3.3	0.3	6.81	6.98
Second series (heat rejection)							
BHE №1 (clay loam)	No. 1 (89.9 h)	33.00	42.1	31.0	24.5	0.73	0.64
	No. 2 (40.7 h)	68.00	55.2	39.3	28.1	1.05	0.85
	No. 3 (21.4 h)	72.00	53.7	45.3	35.6	2.11	1.35
	No. 4 (75.2 h)	96.00	53.7	37.0	30.1	1.42	1.38
BHE №2 (sand)	No. 1 (89.9 h)	33.00	42.1	28.8	25.0	0.61	0.65
	No. 2 (40.7 h)	68.0	55.2	35.6	29.8	0.86	0.91
	No. 3 (21.4 h)	72.0	53.7	40.7	35.7	1.37	1.36
	No. 4 (75.2 h)	96.00	53.7	37.0	30.1	1.42	1.38
Third series (cyclic loads)							
BHE №1 (clay loam)	No. 1 (96.2 h) cooling	171.93	-2.59	7.10	9.29	4.37	4.90
	No. 2 (119.5 h) heating	58.74	50.84	29.32	26.91	0.49	0.60
	No. 3 (141.0 h) cooling	188.09	-1.58	8.81	10.77	4.46	5.16

It should be mentioned that during the first series borehole 2 was shut off, and all the cooling capacity was directed to borehole 1, yet no stationary regime was achieved. This fact is apparently due to the influence of the latent heat of pore moisture freezing on thermal balance of borehole. Experimentally obtained values of "equivalent" thermal conductivity of the soil of 6.8-7.0 W/m°C, are 5.3 to 5.5 times higher than the value of the thermal conductivity of loam in the frozen state, equal to 1.27 W/(m*°C) (Table 1). The results of the first series of experiments in a graphical form are shown in Figure 6.

The purpose of the second series of the experiments was to determine the thermal conductivity of the soil in heat rejection mode. This series included 4 periods; soil in the borehole heat exchangers' models during all the periods was thawed and heated. The water heater was turned on; coolant flow rates for both boreholes were equalized, while temperature of soil and coolant was logged. Before the beginning of the third period, 2 liters of water were poured into the borehole 1, and 4 liters - into the borehole 2. Then before the fourth period, 8 more liters were poured into the borehole 1, and 11 more - into the borehole 2. We note the fact that coolant temperature in the borehole heat exchangers during periods 2, 3 and 4 was almost constant, while soil temperature and specific heat rejection underwent quite regular changes in accordance with the increasing humidity of the soil: specific heat rejection per 1 meter increased, while the difference between soil and coolant temperatures decreased. The results of the second series of experiments are shown in Figures 7 and 8.

A) Heat carrier temperature

B) Ground temperature, 50 mm from BHE

C) Ground temperature, 100 mm from BHE
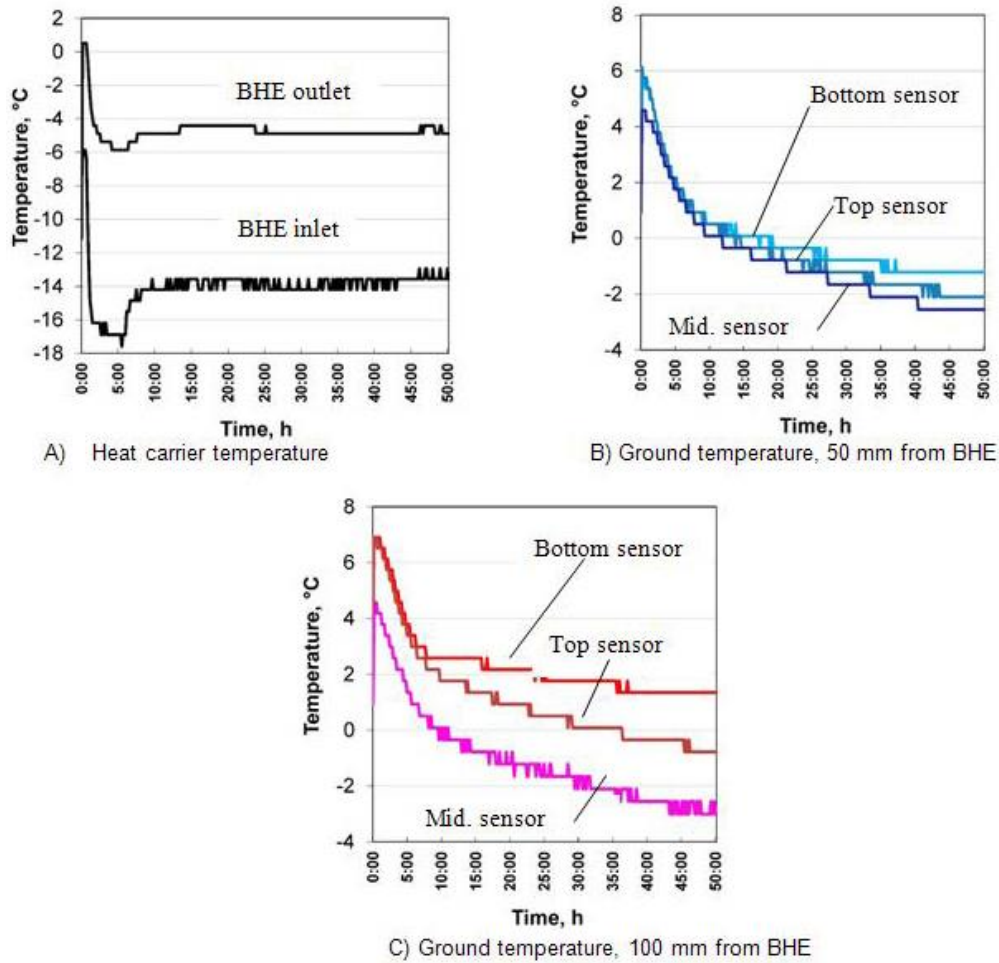
Figure 6. First series results
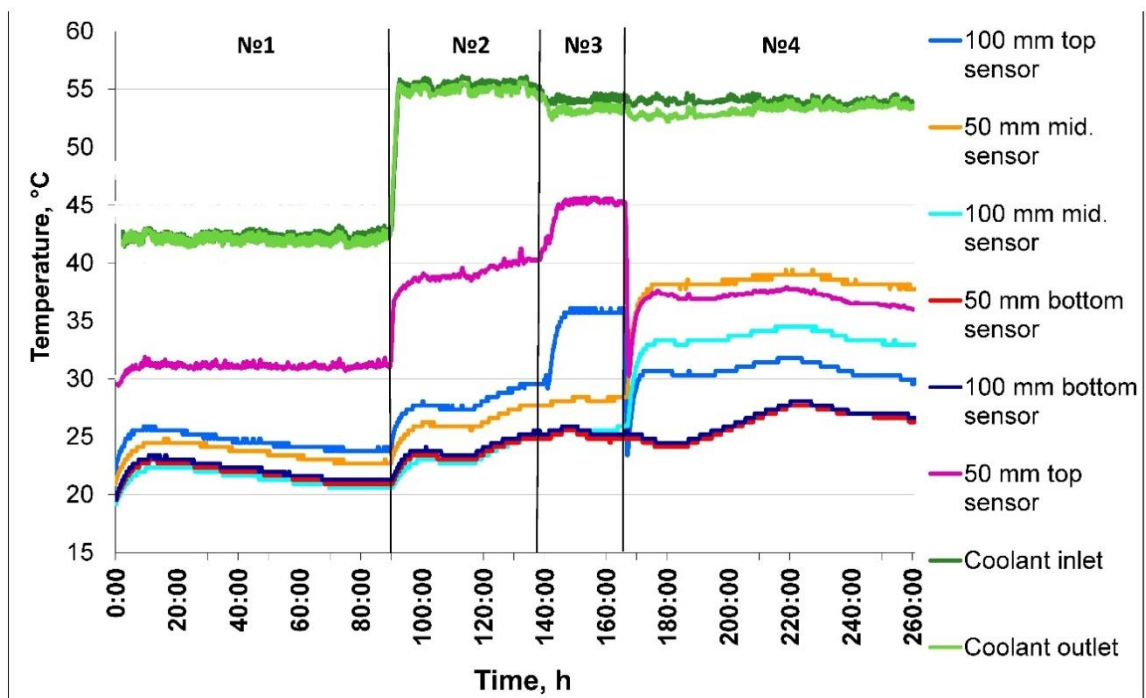
Figure 7. Second series results, BHE No. 1

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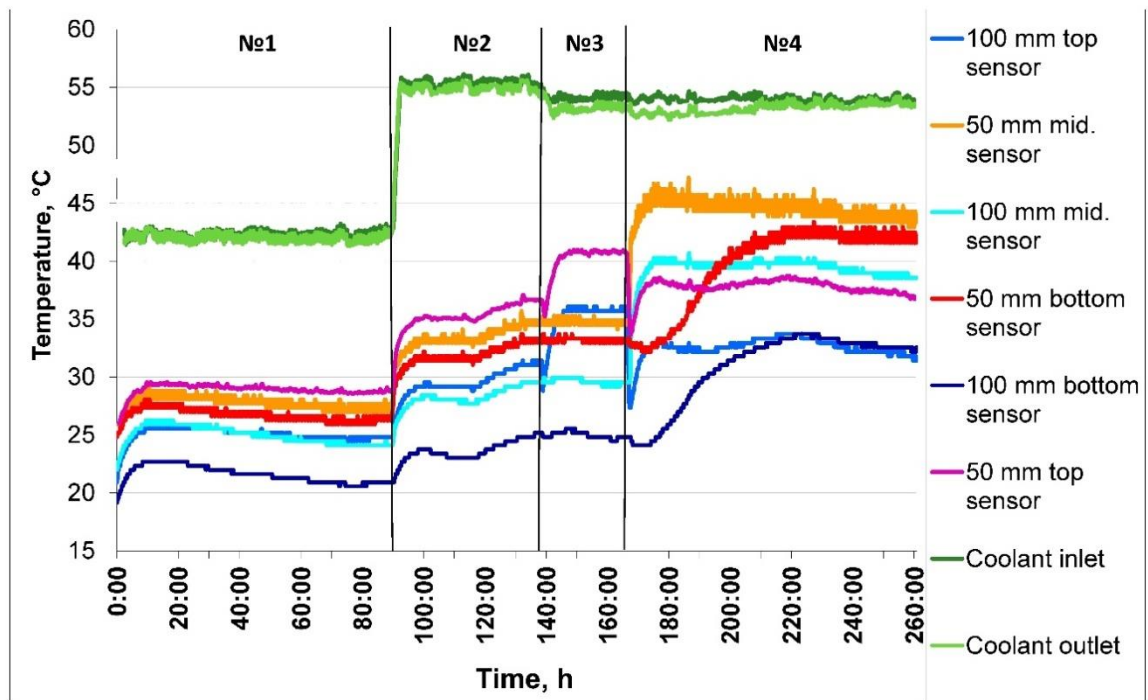
Figure 8. Second series results, BHE No. 2

During the third series of experiments, the impact of cyclic loads (annual cycle) and heat accumulating properties of the ground on its "equivalent" thermal conductivity was studied. The experiments included three periods: the first period - heat extraction - the chiller was switched on; the second period – heat rejection - the electric heater was switched on, and the chiller was switched off; and the third period - heat extraction - the electric heater was switched off and the chiller was turned back on. The results of the third series of experiments presented in Table 2 illustrate the independence of the specific heat gains from 1 meter of the borehole heat exchanger from the cyclicity of the heat load. The results of the third series of experiments are presented in Figures 9 and 10.
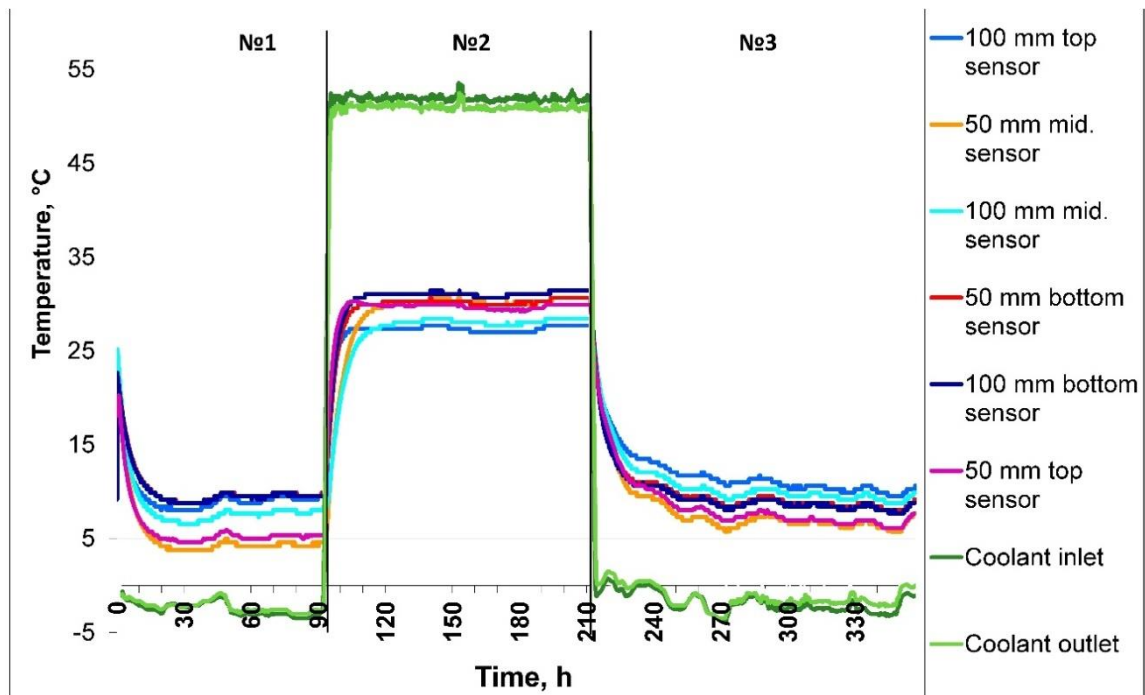

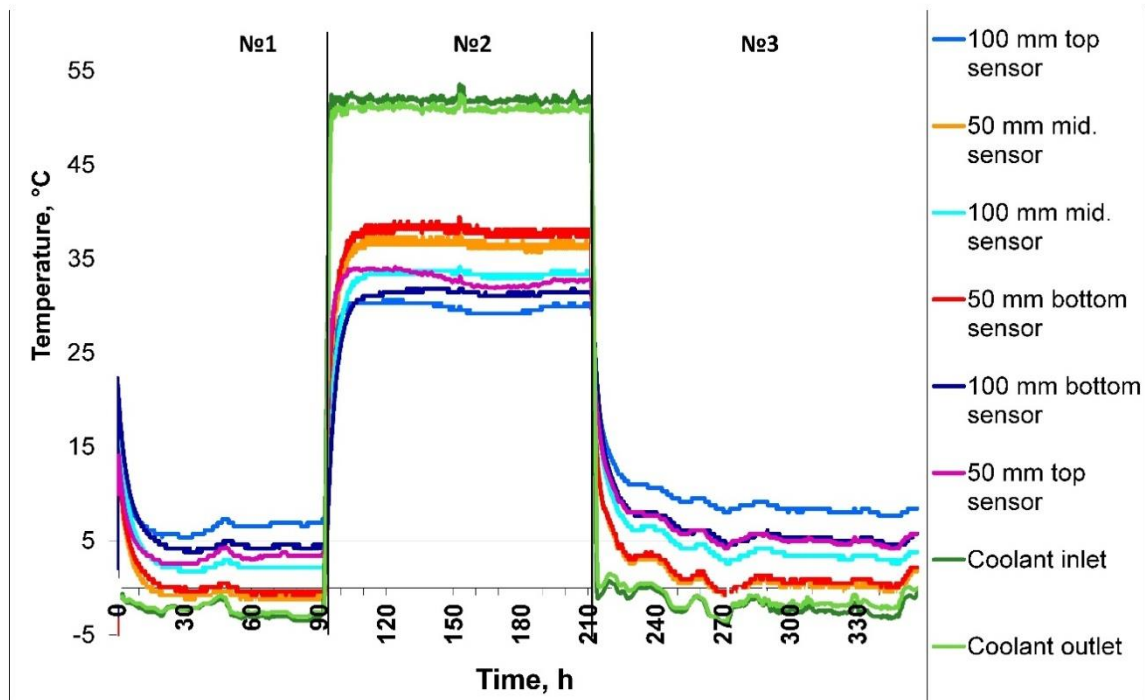**Figure 9. Third series results BHE, No. 1**

Figure 10. Third series results, BHE No. 2

The calculation results showed that accounting for phase transitions of pore moisture in the soil has a significant effect on the temperature of the coolant circulating through the ground heat exchanger. These changes relate to both minimum and maximum temperatures of the coolant in the annual cycle, and taking into account the phase transitions of the pore moisture, the coolant temperature minimums are higher than in the calculation that does not take into account the phase transitions, while the maximums, on the contrary, are lower. The same thermal behavior was demonstrated in [31], where the similar problem of incorporating phase change effects into a final element method software for ground properties simulation was investigated. This observation can be offered the following explanation. At a time when heat is removed from the ground and associated processes of pore moisture freezing are taking place, the latent heat of the phase transition is released during crystallization, which changes the heat balance and leads to higher temperatures of the coolant. At a time when heat from the ground is not consumed and its natural recovery occurs, the frozen ground thaws due to the influx of heat from the external environment. Calculations that take phase transitions into account show that in this case the temperature of the coolant is lower than in calculations without considering the phase transitions. The heat of the phase transition is taken into account in this case with a negative sign, and some of the heat coming from the environment is used to compensate for the latent heat of melting, so not all heat can be transferred to the heat carrier, which leads to lower temperatures.

The general trend of reducing the temperature of the coolant during consecutive heating periods is maintained for both variants of calculation. The temperature of the ground does not have time to return to its initial value over the summer period, and the longer the heat recovery period, i.e. heating period, so, accordingly, less time remains for the restoration of soil, and the stronger this trend will be.

It should be noted that the calculations, taking into account the phase transitions, on average give lower values of the coolant temperature (Fig. 4). The result will be a lower COP of the geothermal heat pump system.

Under given conditions, the ice that formed during the heating period around the boreholes is completely melted only after the first two seasons of operation (Fig. 5).

"Equivalent" thermal conductivity of the soil, taking into account the latent heat of freezing of pore moisture, during the heating period changes significantly and can increase by 2-3 times in comparison with the intrinsic thermal conductivity of the soil.

An important result of the experimental studies, according to the authors, is the fact that the values of the ground "equivalent" thermal conductivity in periods 1 and 3 of the third series of experiments (Table 2) differ from the analogous values obtained in the first series for the heat extraction mode. The

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fact is that in the third series of experiments the soil was in a thawed state. Despite the small negative temperatures of the coolant during periods 1 and 3, the soil temperatures throughout the third series of experiments were positive and freezing of moisture in the ground did not occur. In this case, one would expect that the thermal conductivity of the soil in periods 1, 2 and 3 will be close, since in all regimes the ground is in a thawed state, but in reality we obtained a different picture: the «equivalent» thermal conductivity of the soil in periods 1 and 3 is 8-10 times higher than the thermal conductivity of soil in regime 2. The authors assume that we are dealing with a little-studied effect caused by the condensation of water vapor contained in the pore space of the soil and the related intensification of the heat exchange processes between BHEs and the ground. As it turned out, the influence of this effect on the intensity of heat exchange in the soil can be commensurate and even exceed the effect of freezing / thawing of pore moisture. This effect deserves attention and further study, as it can fundamentally change our current understanding of the BHEs performance.

Conclusions

A new method of accounting of pore moisture phase transitions in the ground during BHE operation is proposed together with mathematical model. The essence of the method is to introduce a new "equivalent" thermal conductivity of the soil, consisting of the direct thermal conductivity of the soil and an additive that is responsible for the freezing / thawing of pore moisture.

The model proposed helps to solve the Stefan problem of heat transfer in a biphasic system with the unknown position of the phase boundary for BHE operational parameters forecast while designing GSHP system simple enough for engineering calculation.

Numerical simulation results show, that accounting for phase transitions leads to lower amplitude of temperature variation of the coolant in the annual cycle while keeping the general trend of reducing the temperature of the coolant during consecutive heating periods. The important thing is that accounting for the phase transitions on average gives lower values of the coolant temperature which will result in lower design COP of GSHP.

"Equivalent" thermal conductivity of the soil, accounting the latent heat of freezing of pore moisture, during the heating period changes by 2–3 times in comparison with the intrinsic thermal conductivity of the soil. If not frozen, ground's "equivalent" thermal conductivity appears to be 8 to 10 times higher in heat extraction mode than in hear rejection. The author's assumption is that the effect is caused by the condensation of water vapor contained in the pore space of the soil. Authors suppose that effect is worth for further study.

Acknowledgement

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