Analysis of ground thermal potential reduction and thermal interaction between boreholes during operation of ground source heat pump in Moscow city environments

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Abstract. Geothermal energy is a renewable energy resource. Nowadays it can be considered as a promising alternative to various fossil fuels. Ground source heat pumps are efficient installations enabling the intensive use of underground energy for heating and cooling of modern residential and commercial buildings. However, climatic conditions often limit the use of this type of installation to a certain extent. This paper presents a description of an existing system comprising a liquid-to-liquid heat pump and a geothermal field consisting of 4 boreholes. The system is used to investigate the intensity of ground temperature potential decrease in winter and its recovery in summer in the Moscow city environment with a detailed study of the properties of individual soil layers, as well as to study the mutual influence of boreholes on each other, represented by the conditional radius of thermal influence of individual boreholes. Graphs of soil temperature changes at different depths are presented.

1 Introduction

Today, a large proportion of the world's energy consumption is for the heating and cooling of buildings. In addition to conventional supply solutions, systems consisting of various combinations of renewable energy equipment are widely used. One of the most common solutions utilising renewable energy sources in heating systems of buildings is the use of heat pumps due to their high efficiency. There are two main types of heat pumps - air source heat pumps and ground source heat pumps. [1] notes that ground source heat pumps have a number of advantages over air source heat pumps. They consume less power to operate; groundwater is a more stable energy source than air; such heat pumps do not require additional heat at extremely low outdoor temperatures; and they use less refrigerant. The main disadvantage of ground source heat pump systems is the high investment cost, estimated to be about 30-50% higher than air source units, due to the extra effort involved in drilling boreholes and arranging geothermal circuit.

Geothermal energy can be used directly or indirectly depending on the temperature of the geothermal sources, which are ranged into low temperature (below 90°C), medium temperature (90-150°C) and high temperature (above 150°C). Usually, the sources with highest temperatures are only used for power generation and are located in volcanic regions. For heat supply in buildings, geothermal energy can be used directly in the temperature range of 35°C to 150°C.

According to [2], the total installed capacity, estimated through the end of 2019 for geothermal direct utilization worldwide is 107,727 MW. The total annual energy use is 1,020,887 TJ/year, a 72.3% increase over 2015, growing at an annual rate of 11.5%. The growth rate of installed capacity and annual energy use over the past 30 years is shown in Fig. 1.

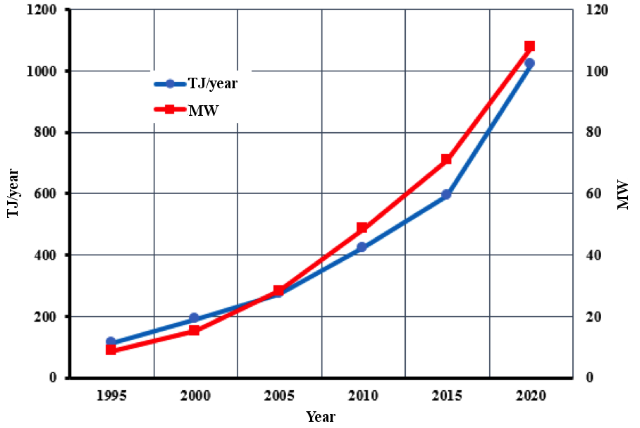


Fig. 1. Installed geothermal capacity for direct utilization and annual energy use from 1995 to 2020.

The steady upward trend in the capacity of geothermal energy systems is primarily due to environmental friendliness as well as high economic efficiency and the highest rates of installed capacity utilisation among renewable energy sources. Despite the variety of different geothermal based heat-consuming systems around the world, the most significant segment of ground energy consumption is building heating systems [3].

Compared to regions with more temperate climates where ground source heat pump systems are widely used, in regions with colder climates and long heating periods, such as 7 months in Moscow, soil freezing around the heat pump borehole in the wintertime is almost impossible to avoid. Also, it should be noted that when using ground source heat pumps to supply buildings with required heat loads a considerable amount of cold is stored in the soil, which can be used in the summer time to cool the building down.

The common recommendations for improvements by drilling deeper boreholes to obtain higher ground temperatures or increasing the number of boreholes to reduce the load on heat pump are often not cost effective. Consequently, for regions with long heating periods, ground source systems should operate at lower coolant temperatures and with the unavoidable drop in ambient soil temperatures below the freezing point of the soil moisture. The authors of [4] reported an experiment in which two heat exchange systems were studied: with low density of ground heat energy consumption - horizontal system of polyethylene pipes of 400 m length and 0.05 m diameter, with high density of ground heat energy consumption - vertical system with one borehole of 40 m depth and 0.16 m diameter. The study demonstrated that with each successive year of operation at the end of the heating period the ground heat energy consumption results in a decrease in the soil temperature around the heat exchanger, and this decrease in temperature couldn't be fully compensated for during the summer period. This effect of reducing the ground thermal potential in the Russian climate is found practically throughout the whole of Russia. Fig. 2 and 3 show the results of zoning the territory of Russia depending on efficiency of low-potential ground heat utilization for heat and cold supply of buildings using horizontal and vertical ground source systems (isograms represent the performance factor equal to the amount of useful thermal energy produced by the system while consuming 1 kW of electric energy, decimal quantity).

Fig. 2. Zoning of the Russian territory according to efficiency of topsoil thermal energy utilization in case of "horizontal" ground source system.

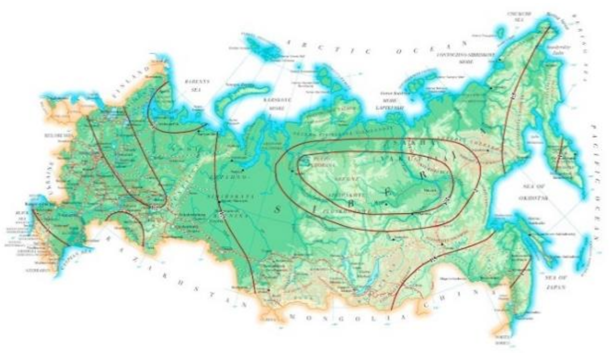


Fig. 3. Zoning of the Russian territory according to efficiency of topsoil thermal energy utilization in case of "vertical" ground source system.

In this paper, the authors describe an existing thermal setup to study the reduction of ground thermal potential in winter and the thermal interaction between boreholes located at different distances from each other.

2 Description of thermal setup

Block 23, one of the blocks of National research university «MPEI», which is a three-storey building with a basement and an annex, is provided as an experimental laboratory.

One of energy sources in the building heating system is a liquid-to-liquid heat pump with a geothermal circuit. This heat pump supplies hot water to heating units and also provides hot water to the building. Mammoth heat pump, whose freon circuit delivers a flow rate of 2.58 m^3/h, was selected according to the specified parameters. The unit capacity for heating is 13.2 kW at power consumption of 3.67 kW, and for cooling it is 12.2 kW at power consumption of 2.71 kW.

The borehole drilling work as well as the geothermal circuit construction and installation work were carried out in order to ensure the operation of this ground source heat pump. The layer distribution of the different soil types over the borehole depth was studied during the drilling work. Main properties of layers are presented in Table 1.

Table 1. Main properties of soil layers.

	Depth [m]	λ [W/m·K]	$a \cdot 10^{-6}$ [m^2/s]
man-made ground	0-15	0.84	0.495
grey clay	15-16	1.60	0.67
loam	16-24	0.87	0.7
black clay	24-31	1.60	0.67
dry silicified limestone	31-38	2.30	1.12
dry limestone with red clay interlayers	38-58	1.95	0.895
red clay	58-60	1.60	0.67

The heat-exchange efficiency depends on physical properties of the soil. According to data given in the table, the average thermal conductivity $a_{avg}=0,746 \cdot 10^{-6}$ m^2/s and equivalent heat diffusivity $\lambda_{eq}=1.287$ W/m·K have been determined, effective borehole thermal resistance is R_c=0.538 m·K/W.

According to the method given in [5], the borehole wall temperature and average fluid temperature values were determined. The borehole length for heat exchange is H=120 m. Total heat transferring from one borehole taking into account heat pump capacity (13.2 kW), compressor current (6.5 A) and supply voltage (380 V) amounts to 2682.5 W. Based on the data obtained, a typical temperature development over time, which has a descending behaviour in heating period and an ascending behaviour in the inter-heating period, was determined (Fig. 4). After the heat extraction stops, the ground temperature starts to recover.

During the first few years of operation the temperature drop during the winter period is quite severe, later on the annual temperature deficit reduces. The recovery period shows a similar behaviour: during the first years the recovery is fast, but with increasing service time the ground temperature recovery time tends to approach zero asymptotically [6].

Thus, with natural ground temperature of 7°C, after one year of operation of the ground source heat pump the ground temperature is restored to 6.6°C by the end of the inter-heating period. This proves that the ground temperature decreases each year at the beginning of each subsequent heating season, and consequently that the ground temperature decreases after the recovery process, i.e. by the end of summer period.

Fig. 5 shows a geothermal field consisting of four boreholes with a total length of 196 m. The boreholes are 60 m, 60 m, 48 m and 28 m deep, with a diameter of 0.15 m for each borehole. Each borehole has a double U-tube with 0.032 m tubing diameter circulating propylene glycol solution and using bentonite as a plugging material. The boreholes are located at different distances from each other.

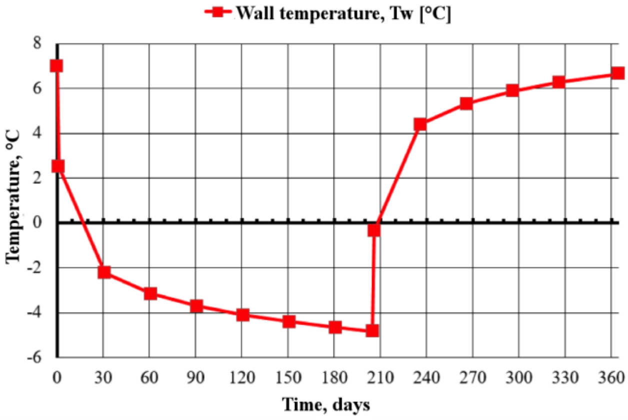


Fig. 4. Variation of borehole wall temperature during the year of operation.

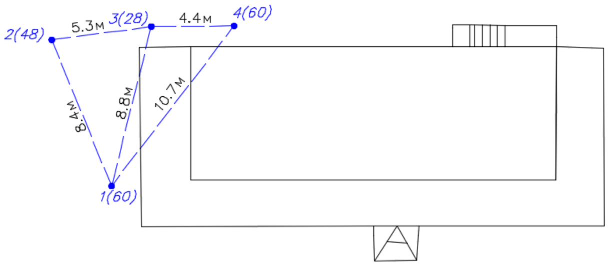
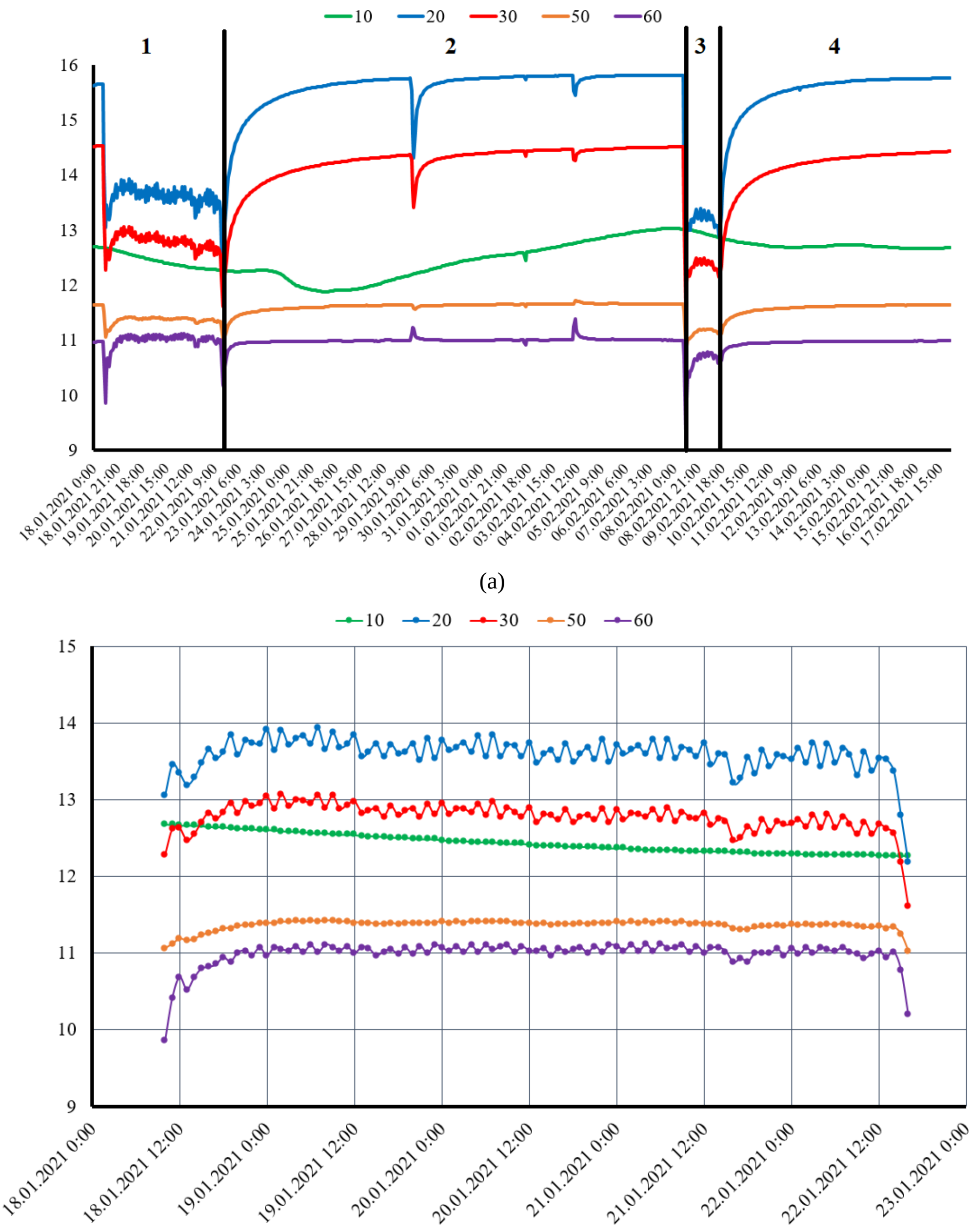


Fig. 5. Borehole arrangement in relation to building.

During installation of the geothermal circuit, five temperature sensors were inserted into fourth borehole with a depth of 60 metres in order to measure the temperature of borehole wall at depths of 10 metres, 20 metres, 30 metres, 50 metres and 60 metres. Fig. 6 (a) shows the variation in readings of temperature sensors, located at different depths of the borehole, during 1 month of operation of the ground source heat pump. The graph shows that the first area corresponds to the heat pump's operating time from 18 to 22 January, after which the unit was switched off. In area 2, the ground temperature potential is recovering. Also, the curve in the area is accompanied by some jumps, which are explained by the brief switching on and off of the heat pump. In area 3 the unit is switched on again from February 8 to 9, while area 4 reflects the switched-off state of heat pump and the ground temperature recovery.

Fig. 6 (b) shows in detail the area of heat pump operation over five days. The curve representing the temperature sensor reading at 10 m depth varies linearly between 12.7°C and 12.3°C. For the 20 m and 30 m depth sensors, the ground temperature ranges from 13°C to 12°C and 12.3°C to 11.6°C, respectively. As for the sensor at a depth of 50 m, there is almost no temperature variation, while reading of the sensor located at a depth of 60 m fluctuates slightly at 10-11°C.



(a)

(b)

Fig.6. Temperature sensor readings at different depths of borehole for observation periods of one month (a) and 5 days (b).

3 Thermal interaction between boreholes

The extraction of subsurface heat energy during long-term operation is accompanied by the effect of "cooldown" of the subsurface volume from which the heat is extracted. This effect means a gradual reduction in the temperature of the subsurface near the borehole walls, which entails a reduction in the heat extracted [6]. This effect is estimated by a conditional radius of thermal influence of the borehole, which increases over time. The diameter of disturbed zone of the temperature field around the borehole depends on borehole diameter, the service time of the ground source heat unit, the temperature and the thermophysical properties of soils and the intermediate heat transfer agent. In theory, circulation of intermediate heat transfer agent should cause variations in soil temperature over an infinitely large distance, but in practice, it is always possible to identify a conditional boundary in the layer of soil, beyond which the natural temperature is preserved, and the temperature field is not disturbed [7]. Nominally, the radius of thermal influence R is defined by relation (1):

$$R = 2.5 \times \sqrt{a \times \tau} \tag{1}$$

a – soil thermal conductivity, m^2/s; τ – time, s.

In this case, according to Figure 7, during a one year of continuous operation, the radius of temperature influence of one borehole will vary from 0.6 m to 12.1 m. At the end of heating period in the first year of ground source heat unit operation with the above-described soil layer distribution, the radius of "cooldown" will be 9 m. The radius of thermal influence will grow steadily and, for example, after two years of continuous operation of geothermal field will increase to 17.1 m. Fig. 7 also shows the variation of the coefficient of heat transfer from subsurface to heat transfer agent, determined by expression (2). At initial moment the heat transfer coefficient will be 4.85 W/m^2·K, and after one year of operation it will decrease to 2.04 W/m^2·K. During further operation, the heat transfer coefficient will not decrease too much and will practically stabilise at 1.9 W/m^2·K during the second year of operation.

$$k = \frac{1}{{D_{bh}}\big/{2 \cdot \lambda_{gr}} \cdot ln\left({R}/{r_c}\right)} \qquad (2)$$

D_{bh} – borehole diameter, v; λ_{gr} – soil heat diffusivity soil heat diffusivity, W/m·K; R – radius of borehole thermal influence, m; r_c – radius of borehole, m.

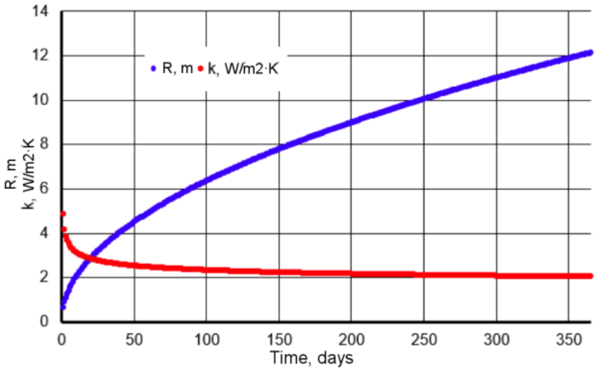


Fig. 7. Variation of borehole temperature influence radius and coefficient of heat transfer from ground to heat transfer agent during one year of operation.

It is worth noting that these dependencies are built for a single borehole system and do not take into account mutual influence of boreholes on each other. Also, these curves correspond to a continuous extraction of heat from the Earth's interior and do not take into account the process of soil temperature recovery in the inter-heating season.

If the vertical borehole is surrounded by other boreholes, the range of heat extraction is limited to half the distance between them. Consequently, the whole soil cylinder surrounding the vertical borehole will be supercooled to some extent if the amount of heat extracted is greater than that discharged into the borehole. In small systems this phenomenon increases and eventually leads to system failure due to freezing of process fluid [8].

Based on the above dependencies, it can be claimed that for the studied multiple-borehole geothermal field the mutual influence of boreholes on each other is observed during continuous operation of the ground source heat pump over a long period of time, as with the existing distance between boreholes there will be overlapping areas of thermal influence of individual boreholes.

In determining the thermal interaction between boreholes, one of the key factors is the soil thermal conductivity. For example, Fig. 8 shows the change in temperature profile as a function of thermal conductivity for different configurations of 4, 6, 9 and 16 boreholes after 1500 hours of continuous operation with a distance of 3 m between the boreholes. After 1500 hours of operation, the performance losses of 4, 6, 9 and 16 boreholes are 26.5%, 32.3%, 38.8% and 45.5%, respectively, with a thermal conductivity coefficient of $1{\cdot}10^{-6}$ m^2/s. The performance loss caused by increasing the thermal conductivity coefficient gradually decreases and the dynamic performance loss for multiple-borehole heat exchangers is generally stable. In addition, the greater the number of boreholes, the earlier this stability will be achieved. As the number of boreholes increases, the thermal interactions between them become more complex, but the dynamic performance loss cannot increase indefinitely. When the number of boreholes is increased from 4 to 6, from 6 to 9 and from 9 to 16, the average performance loss caused by each additional borehole is 2.91%, 2.16% and 0.97% respectively. Fig.9 shows that the effect of increasing the number of boreholes on overall efficiency gradually decreases.

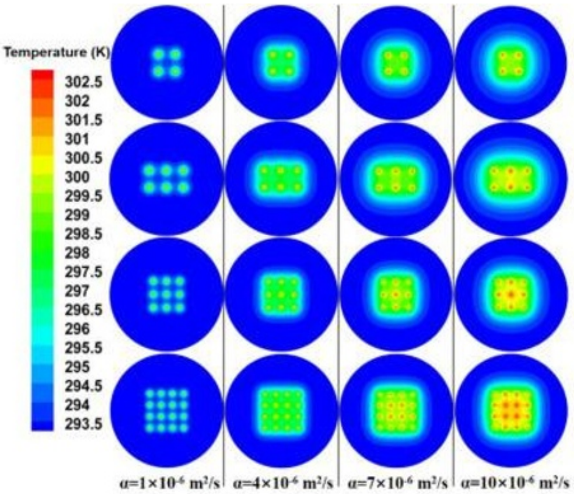


Fig. 8. Temperature distribution around the boreholes for different borehole heat exchanger configurations at different soil thermal conductivities

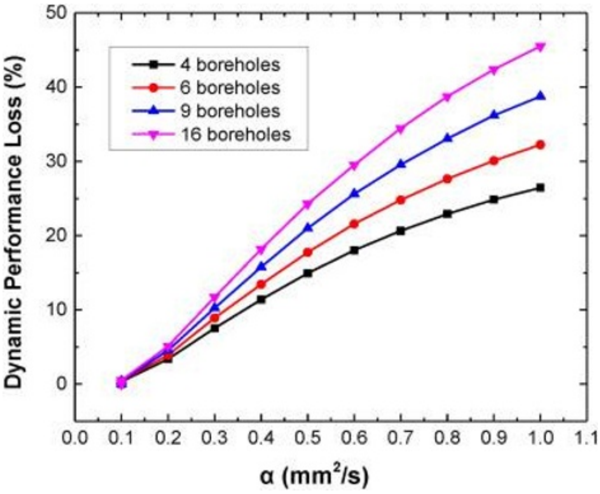
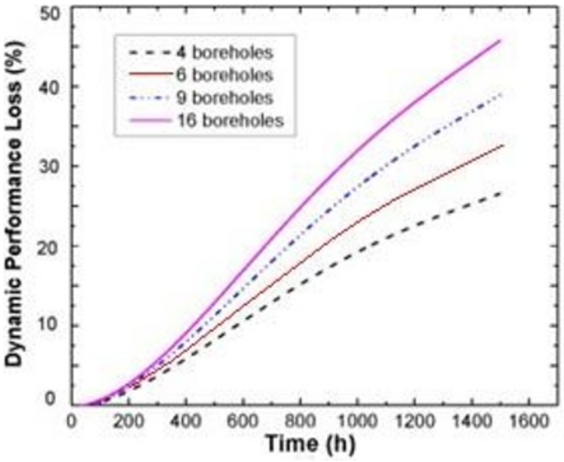
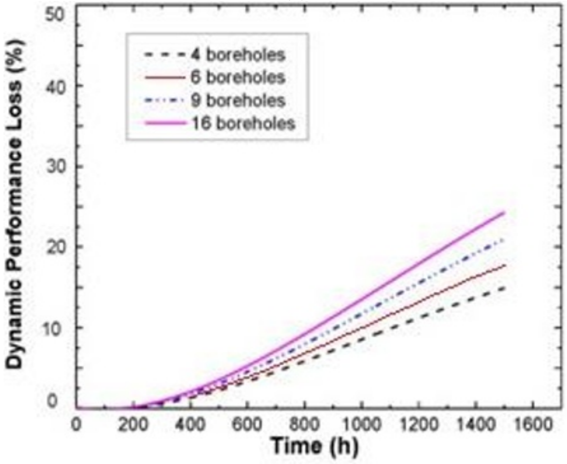


Fig. 9. Variation of dynamic performance loss as a function of thermal conductivity for different number of boreholes

Fig. 10 shows that with a thermal conductivity coefficient of 1·10-6 m^2/s the performance loss starts increasing after 70 hours of operation (a), and with a thermal conductivity coefficient of 0.5·10-6 m^2/s after 200 hours of operation (b). This indicates that the increase in thermal conductivity also shortens the onset time of thermal interaction between the boreholes. However, increasing the number of boreholes has no significant effect on the onset time of thermal interaction [9].



(a)



(b)

Fig. 10. Dynamic performance loss as a function of operating time for a thermal conductivity of $1 \cdot 10^{-6}$ m^2/s (a) и $0.5 \cdot 10^{-6}$ m^2/s (b)

Conclusions

There is a lot of attention being paid to geothermal energy worldwide as the most important clean and renewable energy source. In particular, it is unaffected by weather and climate conditions unlike other renewable energy sources [10]. For geothermal resources and especially their exploitation, the term «sustainability» is often referred to, meaning the ability to maintain production levels over long periods of time.

In the case of combined heating/cooling of a building, the heat balance when using ground source heat pumps is ensured by the system design itself, i.e. the heat extracted in winter is replaced by the heat accumulated in summer.

In the course of this study, the following results were obtained:

- description of an existing thermal setup to study the process of reduction and restoration of the ground thermal potential during operation of a ground source heat unit located in the territory of Moscow is presented;
- during drilling works the distribution of soil layers over the depth of borehole for a given field is studied, the basic properties of soil are determined;
- average values of wall temperature for one well of 60 m depth have been calculated;
- graphs of borehole wall temperature variations at different depths drawn from experimental data obtained during short-term heat pump operation are presented;
- conditional radius of thermal influence R [м] and heat transfer coefficient from the subsurface to the heat transfer agent k [W/m^2·K] for a single-borehole system during continuous operation for one year have been calculated;
- it is found that for a geothermal field consisting of 4 boreholes located at different distances from each other, the thermal interaction between individual boreholes has to be taken into account.

The investigation was carried out within the framework of the project “Efficiency improvement of combined building heating and cooling unit based on renewable energy sources” with the support of a grant from NRU "MPEI" for implementation of scientific research programs "Energy", "Electronics, Radio Engineering and IT", and “Industry 4.0, Technologies for Industry and Robotics in 2020-2022.

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