The Influence of the Ground Thermal Energy and Borehole Heat Exchangers Depth on the Efficiency of Heat Pump (GHSP) Systems in Moscow Geo-climatic Conditions

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***Abstract*—The article presents the results of the numerical estimation of the influence of temperature potential of the geothermal heat energy extracted from the soil with the use of GHSP and borehole heat exchangers depth on the efficiency of the GSHP systems in Moscow and Moscow region geo-climatic conditions. The paper provides the assessment of natural temperature potential of geothermal energy in Moscow region and proposes "typical climatic years" referencing the natural change of average decade and monthly ground temperatures for Moscow geo-climatic conditions. The authors found that consumption of ground thermal energy in specific ground conditions of Moscow region generally results in decreasement of temperature potential of the extracted heat by 5-6 degrees by the 10th year of operation and by the 15th year the process is stabilized. The studies in the paper allow establishing that the borehole heat exchanger GSHP efficient depth for Moscow and Moscow region geo-climatic conditions is close to 60 meters. In this case the temperature potential of the geothermal heat energy extracted during many years of GSHP usage can be expected at the level of 5-10 degrees below Celsius.**

***Index Terms*—Ground source heat pump (GHSP), borehole heat exchanger, ground temperature, typical climatic year, geo-climatic conditions, thermal efficiency**

I. Introduction

The problem of increasing the economic efficiency of ground source heat pump (GSHP) buildings by improving the efficiency of extraction low potential thermal energy from the ground at the moment is one of the most important for the further development of the technology of heat pump geothermal heating systems. Around the world experts are looking for the ways to increase the borehole heat exchanger and the whole GSHP operational efficiency. This way there are a number of works devoted to the optimization of existing designs of ground heat exchangers. For example, the deals with the influence of different materials filling the cavity of borehole heat exchanger on its thermal efficiency. The article describes the options for filling cavities of borehole heat exchanger with solutions based on traditional graphite and bentonite. Possible application of heat-carrying mediums with phase state change, namely CO2, in the U-shaped borehole heat exchangers is considered in the work. [1-3]

The work is devoted to assessing the influence of the ground heat exchanger pipes position in the borehole heat exchanger section on its thermal resistance, and the authors of the article suggest improvements of the dual U-shaped construction in which heat-carrying medium is supplied downwards with the three tubes, and returns through the one. In addition, there is a considerable amount of research dedicated to developing of new designs of borehole heat exchangers. The proposes a new design of borehole heat exchanger, which provides the increase of heat transfer from the ground to the heat-carrying medium of borehole heat exchanger due to natural convection of intermediate heat-carrying medium that fills the cavity of borehole heat exchanger instead of the "traditional" borehole heat exchanger thermal-conducting material. The paper examines the new design of the metal ground heat exchanger presented as an aluminum tube with outer fins. [4] The article is also devoted to the development of new designs of ground heat exchangers, but in contrast to the previous study, the authors suggest the use of an inner fins for the U-shaped heat exchanger tubes. This article deals with the possibility of increasing of the extraction efficiency of geothermal energy by reducing the temperature of the heat-carrying medium that circulates in the borehole heat exchangers, and presents the research results of the optimal parameters of the borehole heat exchanger temperature regime for Moscow geo-climatic conditions selection.

II. Methods

One of the key problems to be solved in the design of ground source heat pump (GSHP) is the search for reliable field data on temperature conditions of the subsurface surrounding borehole heat exchanger of the GSHP. The analysis of the open access publications

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shows that there is no information concerning the typical climatic year referencing the natural change of ground temperatures for Moscow geo-climatic conditions. The data published generally contain the results of ground temperature measurements in Moscow weather stations at a depth of 1.6 m from the ground surface. At the same time, in accordance with the recommendations of the WMO (World Meteorological Organization) the series of data registered at least for 30 years should be used for the formation of the typical climatic data. [5]

Taking this into account the authors of this article have formed "typical climatic year" referencing the natural change of decade ground temperatures for Moscow soil and climatic conditions, which is based on actual observations of ground temperature for the period from 1982 to 2011 years. As basis data the authors used the average decade ground temperatures on a strictly predetermined depth (20 cm, 40 cm, 60 cm, 80 cm, 120 cm, 160 cm, 240 cm and 320 cm) according to the Meteorological Observatory of Moscow State University (MO MSU). From 1955 year continuous monitoring of ground thermal regime is held on eleven different depths. Based on this data the authors calculated ground temperatures on the depth of 400, 480 cm through the Fourier thermal conduction equation. [6-7]

III. Results and Discussion

A. The Effect of Long-term Operation of GSHP in Moscow Geo-climatic Conditions on the Temperature Potential of the Extracted Ground Thermal Energy

Geo-climatic conditions of Moscow, as well as the majority of Russian regions have typically lower (compared to Europe) natural ground temperature and the longer heating period. As the result the long-term operation of GSHP is almost always be associated with the freezing / thawing of ground surrounding the borehole heat exchanger and accordingly with the need to operate borehole heat exchanger in subzero temperatures. On the one hand, this situation leads to a decrease of average power conversion coefficient GSHP, but on the other hand, the rational engineering may increase the economic efficiency of thermal energy extraction from the ground. [8-9]

Let us examine more closely the problem of choosing the rational temperature potential of geo-thermal heat energy extracted from GSHP in Moscow geo-climatic conditions. We will consider as the example a hypothetical detached house with a heated area of 100 square meters and equipped with a ground source heat pump with vertical borehole heat exchangers. Thermal resistances of the exterior building envelope of the house in question are as follows:

- exterior walls – 3,2 m2·h ·°C/W;
- windows and doors - 1,0 m2 ·h.·°C/W;
- coverings and overlaps – 4,0 m2·h·°C/W.

The calculations were performed using the «INSOLAR.GSHP.12» [11] software complex, which simulates unsteady thermal conditions for ground source heat pump (GSHP). [10] During the numerical experiments conduction different variants of geothermal heat collection system with vertical borehole heat exchangers with diameter of 0.16 m and a depth of 40, 60, 80 and 100 m were considered. For every ground heat collecting system configuration the amount of heat collected from one BHE was approximately the same. This fact is shown on Figs. 1-4. The parameters used in the calculations are shown in Table I. [12]

TABLE I. Parameters the Calculations

Parameter	Borehole heat exchanger depth is 40 m	Borehole heat exchanger depth is 60 m	Borehole heat exchanger depth is 80 m	Borehole heat exchanger depth is 100 m
Borehole heat exchanger radius, m	0.08	0.08	0.08	0.08
Borehole heat exchangers depth, m	40.00	60.00	80.00	100.00
Heat-carrying medium flow in borehole heat exchanger, m³/h	4.91	4.16	3.68	3.34
Electrical equipment capacity, kW	3.00	3.00	3.00	3.00
The average (over the period) power consumption during the GSHP operation, kWh	10323.96	9365.74	8842.92	8515.57
The coefficient of heat transfer from the ground to the heat-carrying medium in heat collection system, W/(sq.m. ℃)	100.00	100.00	100.00	100.00
Heat capacity of the heat-carrying medium in the heat collection system, W·h/(kg ·℃)	1.03	1.03	1.03	1.03
The volumetric weight of heat-carrying medium, kg/m³	1049.80	1049.80	1049.80	1049.80
Horizontal thermal conductivity of ground W/(m ℃)	1.00	1.00	1.00	1.00
Vertical thermal conductivity of ground W/(m ·℃)	1.00	1.00	1.00	1.00
The heat transfer from the ground surface coefficient , W/(m ℃)	23.00	23.00	23.00	23.00

Ground heat capacity, Wh/(kg ·℃)	0.80	0.80	0.80	0.80
The ground volumetric weight, kg/m ³	2400.00	2400.00	2400.00	2400.00
The design internal temperature of the room (winter), ℃	20.00	20.00	20.00	20.00
The design outdoor temperature (for example the coldest five days), ℃	-26.00	-26.00	-26.00	-26.00
The duration of the heating season, month	7	7	7	7
The installed electric capacity of the heat pump system (HPS) drive, kW	2.50	2.50	2.50	2.50
HPS condensation temperature (heating), K	323	323	323	323
The thermodynamic efficiency of HPS, the unit share	0.52	0.52	0.52	0.52
Temperature pressure in the HPS condenser, K	5.00	5.00	5.00	5.00
Temperature pressure in the HPS evaporator, K	5	5	5	5
Temperature pressure between the inside air and heat-carrying medium of heating and cooling system, K	15	15	15	15
The installed electric capacity of circulation pumps of heat collection system, Kw	0.30	0.30	0.30	0.30
Efficiency of the circulation pumps of heat collection system, unit share	0.7	0.7	0.7	0.7
The installed electric capacity of circulation pumps of heat fan system, Kw	0.20	0.20	0.20	0.20

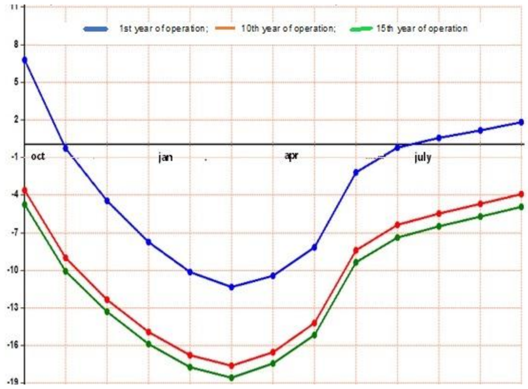

Figure 1. Progress of heat-carrying medium temperature in GSHP borehole heat exchanger with the depth of 40 m

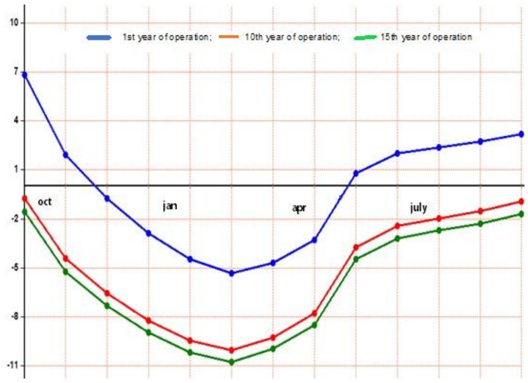

Figure 2. Progress of heat-carrying medium temperature in GSHP borehole heat exchanger with the depth of 60 m

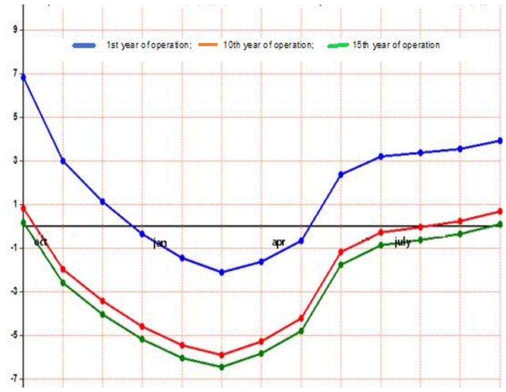

Figure 3. Progress of heat-carrying medium temperature in GSHP borehole heat exchanger with the depth of 80 m

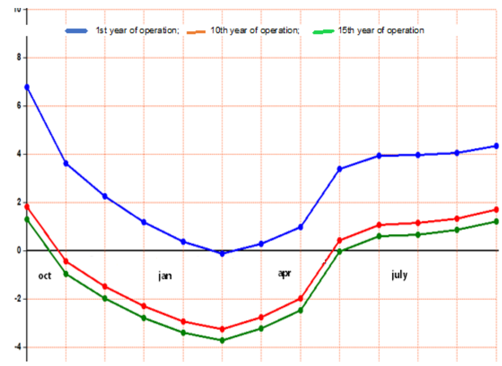

Figure 4. Progress of heat-carrying medium temperature in GSHP borehole heat exchanger with the depth of 100 m

B. *The Economic Efficiency of GSHP Borehole Heat Exchanger Depth Increasing in Moscow Geo-climatic Conditions*

With developed by JSC «INSOLAR-INVEST» computer program «Insolar-NPV.2014.01.01. (The certificate of conformity № ROSS RU.SP15.N00787) was conducted a forecast of net present value (NPV) received by household over the life cycle of 30 years by increasing the depth of GSHP borehole heat exchangers from 40 to 100 m in increments of 20 meters. The main data source for feasibility study was data received via the program «INSOLAR.GSHP.12» and presented in Table 1 and Figs. 1-4. [13-14]

For the calculations using the program "Insolar-NPV.2014.01.01" (The certificate of conformity № ROSS RU.SP15.N00787) certain assumptions were made and macro-economic baseline data was accepted, most important of which are shown in Table II.

TABLE II. PARAMETERS THE CALCULATIONS

Parameter	Value
The average CB RF refinancing rate throughout the life cycle GSHP, %	5
The annual increase in energy rates,%	5
Number of years of operation (life cycle), years	30
The cost of electricity for the GSHP drive at the time of commissioning, the USD / kWh	0.06
Cost of building construction , USD / sq.m	681
The unit cost of borehole heat exchanger depth increase for 1 meter, USD / m	51
Conversion into USD is made at the exchange rate of the Central Bank of the Russian Federation on 02.07.2017	58.7

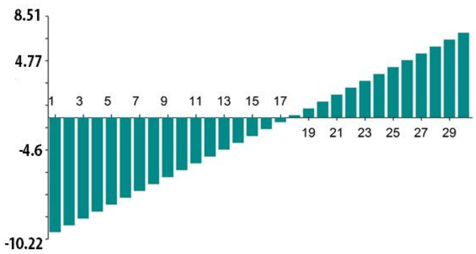

Figure 5. Expected net present value (NPV) of the household for 30 years of GSHP life cycle gained by increasing the borehole heat exchanger depth from 40 to 60 m

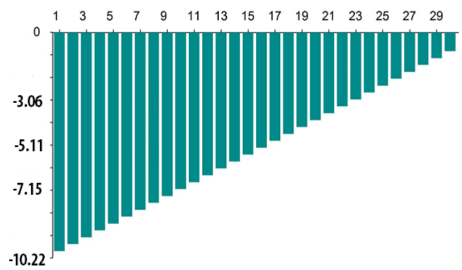

Figure 6. Expected net present value (NPV) of the household for 30 years of GSHP life cycle gained by increasing the borehole heat exchanger depth from 60 to 80 m

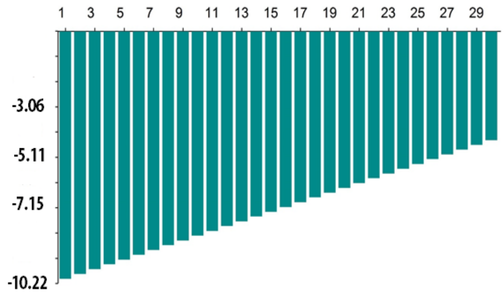

Figure 7. Expected net present value (NPV) of the household for 30 years of GSHP life cycle gained by increasing the borehole heat exchanger depth from 80 to 100 m

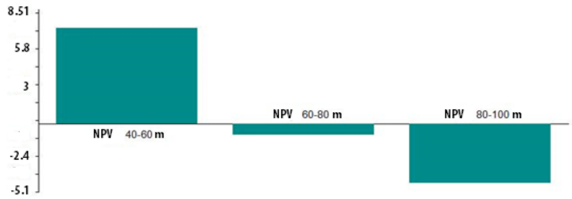

Figure 8. Comparison of net present value (NPV) of household for 30 years of GSHP life cycle, expected from increasing the borehole heat exchanger depth from 40 to 100 m in increments of 20 meters

TABLE III. PARAMETERS THE CALCULATIONS

№	GSHP type	Building energy consumption decreasement generally,%	The total NPV from 1 sq. meter of building, Rub. / sq.m
1	Increase of borehole heat exchanger depth from 40 m to 60 m	9.4	7.13
2	Increase of borehole heat exchanger depth from 60 m to 80 m	5.6	-0.0054
3	Increase of borehole heat exchanger depth from 80 m to 100 m	3.7	-4.41

IV. CONCLUSIONS

The research results presented in this article allowed the authors to make the following conclusions.

1. Moscow and Moscow region geo-climatic conditions are characterized by a significant impact of the GSHP long-term operation on the natural ground thermal conditions that, consequently, leads to a significant reduction of the temperature potential of the geothermal heat energy extracted from the ground. In specific Moscow ground conditions (ground thermal conductivity of 1 W/(m ℃), the heat capacity of 0.8 Wh/(kg ℃), volume weight 2400 kg/m 3) GSHP operation usually causes a decrease of extracted heat temperature potential to 5-6 degrees in 10 years, and by the 15th year the process is set. The difference of temperature potential of extracted geothermal heat at 10 and 15 years of operation is negligible. A quite interesting fact is that during GSHP long-term operation no correlation between the changes

of the extracted heat temperature potential and the depths of borehole heat exchanger was detected.

According to the conducted calculations from the 1st year GSHP operation to 10th year with a borehole heat exchanger depth of 40, 60, 80 and 100 m reduce of extracted geothermal heat temperature potential is almost the same and is 5-6 ℃. It is important to note that the calculations presented in the article were conducted without taking into account phase transitions of interstitial water in a ground when it is freezing and thawing. It seems that inclusion of these processes can slightly reduce the magnitude and intensity of the extracted geothermal heat temperature potential decrease. According to the authors, the actual values of these parameters for Moscow geo-climatic conditions will be in the range of 3-4 ℃ and 5-7 years of operation until steady quasi-periodic regime is set. [15]

2. The results of calculations presented in Table 3 show that increasing GSHP borehole heat exchanger depth from 40 to 100 meters with 20 meters step in Moscow geo-climatic conditions leads to saving of the energy consumed by GSHP drive as follows: when the borehole heat exchanger depth increases from 40 to 60 m - 9.3 %; when the borehole heat exchanger depth increases from 60 to 80 meters - 5.6%, and when the borehole heat exchanger depth increases from 80 to 100 meters -3.7%.

3. The results of calculations presented in Table 3 show that increasing GSHP borehole heat exchanger depth from 40 to 100 meters with 20 meters step in Moscow geo-climatic conditions generates positive NPV to the household only in the interval of depth increasing from 40 to 60 meters and further BHE depth increase is loss-making.[16]

Therefore, the studies in the paper allow establishing that the borehole heat exchanger GSHP efficient depth in Moscow and Moscow region is close to 60 meters. In this case the temperature potential of the geothermal heat energy extracted during the long-term GSHP operation can be expected at the level of minus 5-10 ℃.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This work was conducted by all authors. Vasilyev G.P.-scientific director of the research.

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