Research of the Effectiveness of Using Air and Ground Low-grade Heat for Buildings Heating in Different Regions of Russia

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Abstract. The article presents the results of research on zoning of the Russian Federation based on efficiency of utilization of the low-grade heat of ground and air as well as combinations thereof for heating buildings. When modeling thermal behavior of geothermal HHS in the climatic conditions of various regions of the Russian Federation we considered the effect of long-term recovery of geothermal heat on the thermal behavior of the ground, as well as the effect of the ground pore water phase transitions on the operational efficiency of geothermal heat pump heating systems. The zoning took into account temperature drop of the ground mass caused by many years of heat recovery from the ground. Ground temperatures expected for the 5th year of geothermal HHS operation were used as design ground mass temperatures.

1 Introduction

Today, heat pump heating systems (HHS) are widely used in temperate regions of the world (North America, Europe, and China [1]). Utilization of the Earth surface ground and/or air in HHS as sources of low-grade heat energy is possible almost everywhere. At the same time, the most part of the territory of Russia, in contrast to Europe and North America is characterized by lower natural ground temperatures and rather long-term heating seasons, in connection with what it is practically impossible to recover heat energy from the ground during the heating season with its (ground) positive temperatures.

When operating geothermal HHS, ground mass located within the zone of heat effect of tube register of ground heat exchanger of the ground low-grade heat collection system (heat collection system) is usually subjected to repeated freezing and defrosting owing to seasonal changes in the ambient climate parameters, as well as under the influence of operating loads on the heat collection system. This, of course, is accompanied by change of the aggregation state of moisture contained in ground pores and being in general both in the liquid, and solid and gaseous phases simultaneously. Long-term operation of geothermal HHS in soil and climatic conditions in most regions of the Russian Federation is usually associated with freezing/defrosting of the ground surrounding borehole heat exchangers and these processes should always be taken into consideration when assessing the efficiency of geothermal HHS.

Configuration and type of the most “popular” HHS are usually determined by geoclimatic conditions of the country. So, HHS with water heating systems (mainly floor) [1], providing buildings heating are the most

common in Central and Northern Europe, while heat pumps are more commonly used in air conditioning and air heating systems. [2] The largest number of geothermal HHS are now running in the United States, Canada, Austria, Germany, Sweden and Switzerland. The leader in terms of per capita utilization of low-grade geothermal heat is Switzerland. In Russia, unfortunately, only a few facilities equipped with geothermal HHS are maintained [1].

The Earth's surface ground in geoclimatic conditions in Russia is virtually the only widely available source of low-grade heat energy for heat pump heating systems (HHS). It is known that operation of HHS using the ground heat is usually associated with decrease in temperature potential of the recovered ground heat during the heating season. At the same time, ground low-grade heat collection systems using the “zero curtain” effect are characterized by negative temperatures of the recovered ground heat allowing to use the heat of pore moisture phase transitions in the ground. At the same time, outside air temperatures exceeding temperature of the heat recovered from the ground has been observed frequently during the heating period: thaw periods, transitional periods of the year and simply heating seasons, in which an air temperature exceeds temperature of the heat recovered from the ground.

Despite the huge world practical experience of heat pump heating systems operation, experts still debating about their efficiency in various climatic conditions. Discussions focus on the efficient utilization of various low-grade heat sources, stability of HHS operation throughout the life cycle of buildings, effect of heat recovery from the ground to its natural temperature behavior, etc. [2, 3].

For example, article [3] presents the results of studies performed in the United States and dedicated to assessment of major HHS factors, HSPF (Heating Seasonal Performance Factor) and SEER (Seasonal Energy Efficiency Ratio). HSPF and SEER are defined as the ratio of useful heat output of the heat pump during its normal seasonal use divided by the total electric energy consumed for the season. These studies analyzed efficiency of air heat pumps in the United States climatic conditions on the basis of real data about the operation of more than 9,500 heat pump systems.

Despite the conventional system of climatic zoning in accordance with ARI, the obtained data have not demonstrated homogeneity of efficiency of the air heat pump system inside the climate zones. At the same time, dependence of heat pumps efficiency on the average annual temperature and degree days of the heating season is expressed very clearly. This can be clearly seen on the map of climatic zones of the United States (Fig. 1).

Figure 1. Dependence of heat pumps efficiencies on the average annual temperature and the heating season degree days in various climatic zones of the United States

The map in Fig. 1 shows clearly enough that heat pump systems are most effective in cooling mode than in heating mode in virtually all climatic zones of the United States.

The authors analyzed the experience of US data obtained in the article [3] and made the chart of dependence of the seasonal performance factor on the heating season degree hours.

Based on the analyzed data, the authors of [3] plotted the chart of dependence of Heating Seasonal Performance Factor on the heating season degree hours, shown in Fig 2. The chart clearly shows a tendency to HHS efficiency decrease with increase in number of heating season degree days.

2 Zoning methodology

Research of research on zoning of the Russian Federation based on efficiency of utilization of the low-grade heat of ground and air for heating buildings, presented in this paper are based on the assessment of efficiency of

geothermal HHS utilization in climatic conditions of Russia [6] previously performed by its authors. In this paper, an efficiency criterion for heat pump heating systems was the climatological factor DH_{hps} ,

numerically representing the number of degree hours of HHS operation in the year. This parameter is actually an analogue of well-known and widely used parameter of degree days or degree hours of the heating period, but takes into account the effect of climatological parameters on the HHS coefficient of performance (COP). Independence of the proposed climatological factor on heat protection and other characteristics of the building is an important aspect. In general, climatological factor DH_{hps} can be determined by the following formula, degree hours:

$$DH_{hps} = (T_k - 273 - h_i - t^{cp}_n) \times z \times (T_k - T_u) / (T_k \times \eta) \quad (1)$$

Figure 2. Dependence of Heating Seasonal Performance Factor on the heating season degree hours

where:

T_k – coolant temperature at the HHS outlet and the heating system inlet, K;

h_i – temperature difference between coolant at the heating system inlet and the inside air;

t^{cp}_n – outside air temperature averaged per heating season, or the HHS operation period, is taken according to SNiP “Building Climatology” [2].

z – duration of the heating season or the HHS operation period of the year, is taken according to SNiP “Building Climatology”, hours, [2]

T_i – average temperature of the low-grade heat source for the heating season or for the HHS operation period, K. According to SNiP “Building Climatology” [2] it is equal to:

-for geothermal HHS with vertical BHEs: it is equal to the average outside air temperature increased by 1 degree

-for air systems: it is equal to the outside air temperature averaged for the heating season or the operation period;

-for combined systems: it is equal to the temperature averaged for the period of operation of each of the low-grade heat sources.

Average value η was taken equal to 0.469914 for ground, and 0.33652 for air

Values η are presented in accordance with the data of EN 14511 for the considered modes. The other used values (t^{cp}_n , z , T_u) are presented in SNiP 23-01-99 “Building Climatology”. [2]

Zoning was performed based on two values **Tk = 308 and 323 K (35 and 50 °C)**. These values correspond to the standard design modes for heat pump systems established by the European standard EN 14511. Value Tk = 308 K corresponds to floor and air heating systems.

Value h_t is assumed to be equal to **15 degrees** for Tk=308 K and equal to **30 degrees** for Tk=323 K.

According to values introduced by the formula, zoning based on climatological factor was performed. Low-grade heat source - ground. (Figs. 3-4.) Mapping was carried out for all regional centers of Russia with the use of software MapInfo Professional 10.5.

In the case of using air as the low-grade heat source, climatological factor DH_{hps} is determined by the formula 2

$$DH_{hps} = \sum_{i=1}^n (T_k - 273 - h_t - t_{u,i}^{cp}) \times z_i \times (T_k - T_{u,i}) / (T_k \times \eta) \quad (2)$$

where $-i$ - number of the period of use of the low-grade heat source, and n – number of periods of use of various sources in the year. If the source is used several periods in a year, each of the periods is assigned a number. As for the ground (as a comparison), when calculating values for air, the entire heating period by months for each city of Russia was taken conditionally.

According to values introduced, zoning based on climatological factor was performed. Low-grade heat source - air. (Figs. 5 -6.)

In the calculation of the combined use of heat sources “air+ground” for each city we used the heating period conditionally divided into ground and air, where the minimum air temperature was -5°C because at lower temperatures the use of air as a heat source is not effective and the authors suggested that at low temperatures the system will switch to ground. In the case of using combination of low-grade heat sources, climatological factor DH_{hps} is determined by the formula

(2) too.

In carrying out these calculations for each administrative center of all Russian regions, we determined periods of use of each of the low-grade heat sources according to the efficiency of use: ground in the lowest values of outside air average daily temperature, air in the warmest days (up to -5°C). [5] According to these data, zoning based on the combined use of low-grade heat sources was performed. (Figs. 7-8.)

Figure 3. Zoning of the Russian Federation based on Tk=308, $h_t=15$ degrees. Low-grade heat source - ground.

Figure 4. Zoning of the Russian Federation based on Tk=323, $h_t=30$ degrees. Low-grade heat source - ground.

Figure 5. Zoning of the Russian Federation based on Tk=308, $h_t=15$ degrees. Low-grade heat source - air

Figure 6. Zoning of the Russian Federation based on Tk=323, $h_t=30$ degrees. Low-grade heat source - air

Figure 7. Zoning of the Russian Federation based on Tk=308, $h_t=15$ degrees. Low-grade heat source - air+ground

The calculations allowed to obtain climatological factor that allows to determine the utilization efficiency criteria for various heating systems for each region of Russia. To get the value of the actual energy consumption of a heat pump system for heating and ventilation, it is necessary to determine the specific characteristic of the building heat consumption for heating and ventilation, for

example, according to SP 50.13330.2012. “Thermal protection of buildings” $q_{отр}, W/(m^2 \cdot ^\circ C)$ and multiply it by a climatological factor DH_{hps} . [5, 6]

Figure 8. Zoning of the Russian Federation based on $T_k=323$, $h_t=30$ degrees. Low-grade heat source - air+ground

The results obtained were tested in the mode of air conditioning of buildings, which were carried out in field conditions at the real facility - a hotel complex in Olginka village, Tuapse. To conduct research based on the hotel power supply system, an intelligent pilot heat pump energy complex was created, including experimental heat pumps and systems of low-grade heat collection from ground and air.

3 Conclusions

Analysis of the results of numerical experiments leads to the conclusion that utilization of outside air in combination with the ground as a heat source for low-grade heat pump evaporators of the designed energy complex in the climatic conditions in Moscow and southern part of Russia is very effective. Energy saving in the application of this solution is from 13% in the climatic conditions in Moscow and 20% in southern regions of Russia.

An important feature of the results obtained is the possibility of their use in mass residential, cottage and commercial construction. Today, tens of thousands of buildings and commercial facilities (shops, stalls and so forth) are equipped with air-conditioning systems operated in winter as heat pumps for rooms heating. However, operation of air conditioners in this mode is physically possible and economically effective only until the outside temperature is above minus 15 $^\circ C$. At lower temperatures, air conditioners are actually disabled and back-up heating system is required. Technical solutions developed in this article allow to solve this problem by switching to another low-grade heat source - the Earth's

surface ground at low air temperatures. As a result, the developed intelligent heat pump energy complex can be effectively used all year round, both in heating and in air conditioning mode. Studies have shown that switching a heat pump evaporator from ground to air in such moments will allow 20% reduction in the required number of BHEs of a ground low-grade heat collection system, the cost of which now stands at more than 50% of the whole geothermal heat pump heating system. This provides more than 15% energy savings in comparison with HHS using only ground as a source of low-grade heat.

These data demonstrate that efficiency of ground utilization as a low-grade heat in our country is higher than efficiency of air and combined ground and air utilization, but in the south regions, these values are almost equal. [4-6]

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