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### System approach to evaluation of the building heating efficiency using geothermal heat pump in the climatic conditions of Western Ural

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Abstract. The current paper is devoted to the estimation the effectiveness of the application of the geothermal heat pump application in the climatic conditions of Western Ural. The system approach for assessing the efficiency of the heating system of the research unit (model of a residential house) on the basis of the heat pump is proposed. This approach involves multicriteria analysis of the facility operation based on the data of field experiments and simulation results, as well as evaluating the economic efficiency of the heat pump as compared with traditional heat sources.

#### 1. Introduction

According to the current economic estimates, it is considered that in countries with a cold climate, to which Russia belongs, it is appropriate to consider the use of geothermal heat pumps (GHP) using ground as a source of low-potential heat. Such pumps are well proven for year-round use. Heating of the building with GHP involves the use of thermal energy stored in the ground or in water with a small consumption of electrical energy. Since the soil temperature is virtually constant throughout the year, the Heat Transfer Coefficient Conversion (HTCC) throughout the year is a constant value ranging from 3 to 4.5.

In Perm National Research Polytechnic University (PNRPU) in cooperation with the Ministry of Industry of Perm Krai, a project of the creation of the energy-efficient autonomous research module (EEARM) with a GHP and a building dispatching system was developed and implemented. In this building, the high-tech development of the PNRPU in the field of energy and resource saving is concentrated, which makes it possible to use this facility to develop full-scale experiments of the renewable energy sources use, including GHP, in the climatic conditions of the Western Urals (Figure 1) [1].

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The structural design of the research module is a frame with the use of glued wooden structures (GWS) as supporting columns, beams and floor panels of the full factory assembly. External walls are frame, filled with mineral wool Rockwool Light Batts (Figure 1). Windows are panoramic, wood-aluminum European standard (Euro-windows of the 4th generation) with tempered, low-emission glass. Roof is pitched and is made from profiled sheet. The total area of the building is 200 m<sup>2</sup>. Taking into account the heat losses, which amounted to 15 kW, the building on energy efficiency corresponds to class B (high).

Calculated outdoor temperatures for the design of the heating system were adopted in accordance with SNiP 23-01-2003 "Construction climatology": for the cold period – To = -35 °C; for the warm period – To = 21.8 °C; duration of the heating period is 229 days.

Functionally, the module is divided into several units: meeting room, showroom, lecture room, boiler room, server room.

A system approach to assessing the efficiency of heating EEARM with the use of a geothermal heat pump (GHP) provides for a multicriteria analysis of the building functioning from different points of view, combined with an integral indicator of energy efficiency, based on the results of field experiments and simulation results [2].

## 2. Formalization of the task of energy-efficient management of the heat supply system for EEARM

Let's describe the models of heat supply control for each *i*-th building premise at given environmental parameters  $-E_i$  and room parameters  $I_i$  with the following vector:

$$M = \left\{ f_{ij} \left( E_i(t), I_i(t) \right), i = \overline{1, m} \right\}, \tag{1}$$

where  $f_{ij}$  – function that determines the dependence of the control parameters for a given *j*-th temperature in the *i*-th room; *m* – number of heated premises in the building.

We shall establish the limitations on the thermal energy supply at each instant of time on the interval T:

$$\forall t \in T : Q_i \in [\underline{Q}_i, \overline{Q}_i] i = \overline{1, m}$$
(2)

and the total limit on the amount of energy used:

$$\sum_{i=1}^{m} \int_{t \in T_i} Q_i(t) dt \le Q_0$$
(3)

where  $\underline{Q}$ ,  $\overline{Q}$ - lower and upper limits of the supplied heat energy to the room;  $Q_0$  – maximum volume of thermal energy of all sources in the *T* interval of time,  $T_i \subseteq T$  – time interval of heating of the *i-th* room.

Let's write down the control parameters that are required to solve the problem of energy-efficient heating control of the *i*-th room at the *j*-th indoor air temperature, as vector P:

$$P = \left\{ P_{ij}, i = \overline{1, n} \right\},\tag{4}$$

where n – number of values of the air temperature in the room.

The target value of the indoor temperature at the time interval under consideration can be written as:

$$Temp = \left\{ Temp_{j}, i = \overline{1, n} \right\}$$
(5)

The results of the control functions implementation for models M(1) using S scenarios for given constraints (2) and (3) will be described by the following tuple:  $K = \langle M, S, Q \rangle; i = \overline{1, m}; j = \overline{1, n}$ . In this case, the scenarios describe the algorithm for solving the problem of supplying the coolant to the building premises at the target air temperature values (5).

At the same time, the optimal result of the EEARM heat supply system management will be achieved with minimal energy costs:

$$K^* = \sum_{i=1}^{m} \int_{t \in T_i} \mathcal{Q}_i\left(t; P_{ij}\right) dt \to \min(\mathcal{Q}_i)$$
(6)

The optimal distribution of heat energy through the premises is achieved due to the established

control parameters ij described by the most rational scenario S\*. The implementation of this scenario can be achieved with the help of heat management controllers using expert knowledge that describes the nonlinear dependencies of the target temperature values and the amount of thermal energy used for the specified building parameters [3, 4].

#### 3. Management of the heat supply system of the EEARM and monitoring of its operation

To ensure the objective function (6) with the help of the built-in automation system, scenarios for controlling the building heating according to the coolant temperature and the indoor temperature were realized.

The "indoor temperature" control script provides minimum heat energy consumption in relation to other management scenarios, including "season management", "day-time management", "day-of-week management", "coolant temperature control". In this case, to ensure a constant set temperature within the control room, the heat transfer temperature of the system is controlled by a heat pump. When the set temperature in the room is reached, the heating is reduced and the set air temperature is maintained. This controls the temperature of the coolant at a constant pump output. Such a system effectively operates at different ambient temperatures outside the heated room. However, with good thermal insulation of the room, there will be inertia, since the sensor inside the room will later react to the temperature change from the outside.

The relative savings in the consumption of heat energy for heating the premises during the heating period can be calculated by the following expression:

$$\Delta Q = \frac{|Q_1 - Q_2|}{Q_1} \cdot 100\%,$$
(7)

where  $Q_1 = L \cdot c \cdot (t_0 - t_n)$  – heat consumption, W; L – volume flow of coolant, m<sup>3</sup>/h; *c* – specific mass heat capacity of coolant, J/(kg°C);  $t_n$  – cooled coolant temperature, °C;  $t_0$  – temperature of the heat medium supplied to the heat pump, °C.

To assess the operation of the heat supply system of the research module with the embedded algorithm, data were collected from the coolant temperature sensors in the inlet  $(t_{\pi})$  and output  $(t_0)$  piping of the heat pump and the environment  $(t_{oc})$ .

From 01.03.2017 to 13.03.2017 and from 19.03.2017 to 02.05.2017 the monitoring of the implementation of the scenario "control over coolant temperature" was carried out. The results are presented in Figure 2 and 3. He volumetric flow of the heat carrier is taken as a constant value. The data visualization is performed in the OpenJEVis – a specialized software product for processing and visual analysis of energy data [5, 6].



**Figure 2.** Monitoring results of coolant temperature and ambient temperature, interval A – control scenario disabled, interval B – scenario "control by coolant temperature"

Figure 2 shows that the temperature change  $(t_0-t_{\Pi})$  when the script does not occur, i.e. thermal energy is continuously fed into the room with a constant value. Besides, according to Figure 3, it is evident that the temperature change  $(t_0-t_{\Pi})$  occurs at the time when  $t_{oc}$  is below zero, which corresponds to the control scenario. If, in the first scenario, the temperature difference was approximately 20 °C at an ambient air temperature of 7 °C, then with the activation of the second scenario the difference is only 3 °C at the same external temperature.



**Figure 3.** Results of monitoring the temperatures of the coolant and the environment, the control scenario "on the temperature inside the premises"

Taking into account the constant flow of the heat carrier and using expression (7), it is easy to estimate that the use of the second scenario gives an almost 7-fold effect on saving thermal energy under the given conditions of experimental studies. In particular, for the sampling of the statistical data presented in Figure 2, using the expression (7), the relative savings of the heat consumption during the operation of the "coolant temperature control" scenario reaches 23 %.

#### 4. Calculation of the effectiveness of the use of GHP from the economic point of view

To calculate the economic efficiency of the heat pump in the long term, an analysis of the growth in tariffs for electricity and gas supply for the period 2010–2017 was made. The average value of relative growth rates for electricity was -7.17 % for the gas -8.35 %. These values were used for further calculations as indicators of the average annual growth in the cost of tariffs for electricity and gas.

Calculation of heating costs was carried out for two scenarios: first -100 % heating of the building's areas, the second - reducing the temperature in the unattended building premises to 9 °C, the total area of which reaches 50 % of the total area.

As a result of the analysis of the data obtained, it can be concluded that, from the point of view of economic efficiency, the use of an electric boiler for a heat supply system is inexpedient; the costs for a heating period will be several times higher than using a heat pump or a gas boiler. If there is an opportunity to connect to gas supply, the heat supply system based on a gas boiler is the most cost-effective source of heat supply. At the same time, a heating system with a heat pump produces a good economic effect, is safer compared to gas, and environmentally friendly.

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Figure 4. Dynamics of heating costs increase for EEARM in 2010–2018, and the forecast for 2019–2030

#### 5. Conclusion

Based on the results obtained, the following conclusions can be drawn:

1. The implementation of the scenario "control by coolant temperature" gives a relative saving of heat consumption up to 23 %.

2. The use of the building dispatching system in the management of the heating system allows efficient distribution of heat energy through the premises for various purposes with the provision of reduced internal temperatures in 50 % of the premises, which allows to reduce the integral energy consumption of the building by at least 30 %.

3. With the further growth of tariffs for energy carriers, in particular gas, the use of a heat pump can become an alternative to traditional energy sources, in particular, the cost of energy supply of 50% of the building volume with a heat pump is comparable to the cost of full-scale heating using a gas boiler. In this case, the heat pump is a safer source of heat.

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