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Rational Modes of Heat Supply Using a Hybrid Heat Generating Plant Based on a Geothermal Circulation System, Heat Pump and Boiler Installation

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ABSTRACT

The study presents the modeling of heat supply modes using a hybrid heat-generating plant based on a geothermal circulation system with thermal and high-thermal waters, a heat pump and a boiler installation in order to determine the rational parameters of the operation system. The aim of the study is to determine the optimal replacement of fossil fuels with geothermal energy, under which the consumer will receive a heat carrying agent of high quality. At the same time, the operation of the heat-generating plant will be characterized by optimal indicators of energy efficiency.

1. INTRODUCTION

The development of geothermal resources for the needs of heat supply is a perspective direction of thermal power in Ukraine. The average temperature gradient of geothermal resources in Ukraine is 0.02-0.05 ºC/m, and the temperature of thermal waters and rocks is 20-70 ºC at the depth of 1 km and 40-135 ºC at the depth of 3 km (Karpenko et al., 2013). The most promising for the development of geothermal thermal power is the territory of the Dnipro-Donetsk cavity, Carpathian, Transcarpathia, Southern Ukraine and Crimea (Shidlovsky, 2007; Starodub et al., 2012).

Insufficient high temperature of thermal waters, the probability of their temperature lowering at the mouth of production wells and changing the flow rate during the operation period (Dyadkin, 1989; Lokshyn, 1974) require the inclusion of the geothermal heat and power unit, a peak preheater or a reserve heat source to the thermal scheme. Such heat generating units can be boilers, heat pumps, electric heaters, etc.

Conditionally, constant temperature of thermal waters at the output from production wells determines the specificity of the regulation of the release of thermal energy in geothermal heat supply systems (Lokshyn, 1974; Gadzhyev, 1984; Bugai and Redko, 2013). In addition, heat consumption for heating systems depends on the temperature of the outside air, and for hot water supply systems – from time of the day and day of the week. Supplying to consumers of qualitative heat with parameters not lower than estimated depends on the modes of release of thermal energy from the source. It is also important to ensure the energy and economic efficiency of the system, to minimize harmful emissions to the environment, energy and resource conservation, when applying several heat sources and their corresponding heat generating units to the heat station, besides of the compliance of produced heat energy for consumption.

2. OBJECTIVE

The aim of the work is to develop a mathematical model of thermal energy release modes from a hybrid heat source containing a geothermal circulation system, a heat pump and a boiler plant for heating purposes. Using mathematical model it is supposed to define and substantiate rational heat supply regimes, the share of each heat generating unit in providing of thermal energy and other parameters of the hybrid heat source.

3. MAIN RESULTS

In figure 1 a diagram of a hybrid heat station which contains a geothermal circulation system, a heat pump and a boiler installation is shown.

In a geothermal heat exchanger, the heating of the network water of the heating system can occur at low external temperatures, which are characteristic of beginning and end of the heating period. If the temperature potential of the thermal fluid is insufficient, the heating of the network water to the temperature corresponding to the temperature curve can be provided by the heat-pump unit. If the temperature of the network coolant in the supply pipeline of the heat supply system should be higher than the condensation temperature of the heat-pump unit, then its heating to the required temperature is carring out in the boiler plant. For more effective regulation of the thermal power release to the heat supply system a parallel-sequential connection of three heat generating units within the heating station is used.

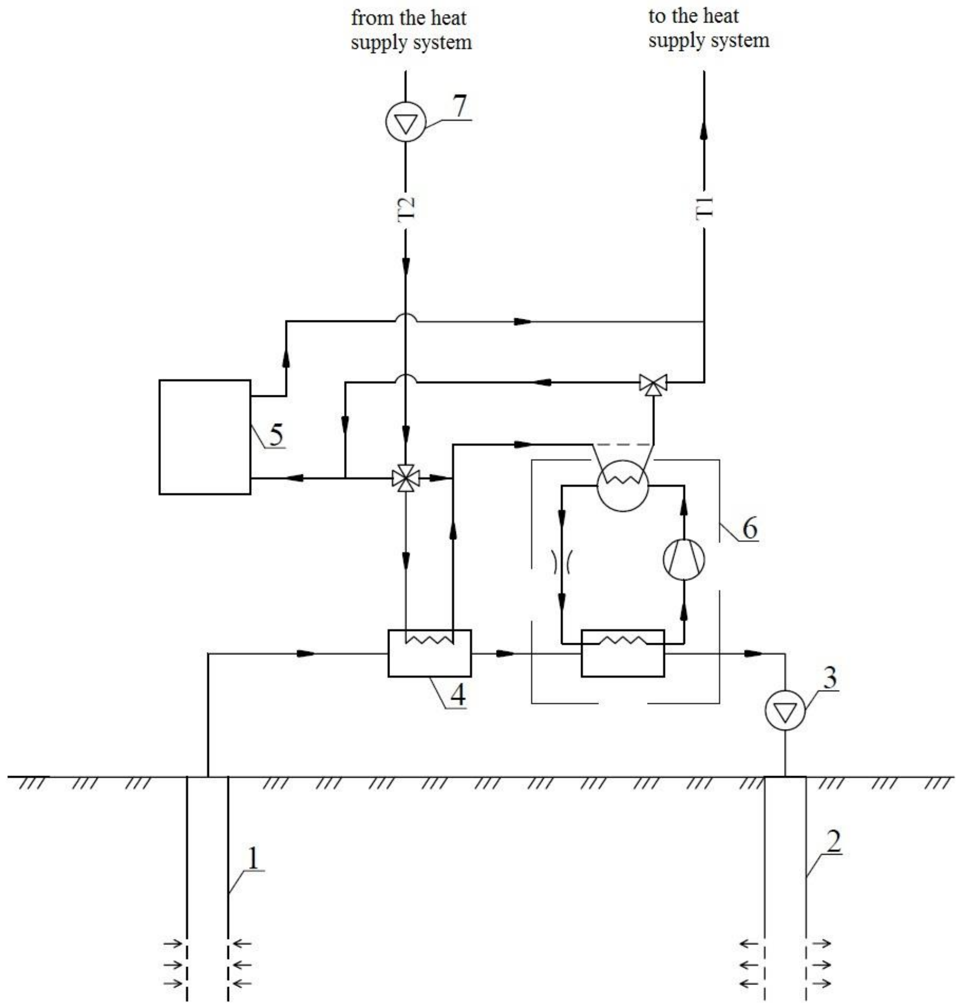

Figure 1: A hybrid heat station based on a geothermal circulation system, a heat-pump unit and a boiler plant: 1 – production well, 2 – an injection well, 3 – a injection pump; 4 – geothermal heat exchanger; 5 – boiler installation; 6 – heat-pump unit; 7 – the network pump of the heat supply system

The release of heat into the heat supply system from a geothermal source can be carried out with varying flow rates of the thermal fluid, depending on the heat supply needs i.e. quantitative regulation, or at constant consumption, which requires the installation of devices for the accumulation of thermal energy.

Do consider the work of the heat station for the quantitative regulation of the release of thermal energy from thermal water to the network water.

Providing only the work of geothermal heat exchanger for the heat supply system, the flow of the thermal fluid is based on the formula below:

$$G_g(t) = \frac{Q(t)}{c\left(t_g{'} - t_g{''}\right)}, \tag{1}$$

where t – external air temperature, ºC; Q (t) – heat load of the heat supply system, depending on the temperature of the outside air, kW; c – heat capacity of the thermal liquid, kJ/(kg · K); t_g '– temperature of the thermal liquid at the input to the geothermal heat exchanger, ºC; t_g '' – temperature of the thermal liquid at the output from the geothermal heat exchanger, ºC.

$$\tau_1(t) \le t_g' - 5, \tag{2}$$

where $\tau_1(t)$ – the temperature of the network water in the supply pipeline, depending on the temperature of the outside air, ºC.

If the supply pipeline of the heating system needs higher temperature of the network heat carrier that does not exceed the condensation temperature in the condenser of the heat pump, thermal energy supply is possible using two heat generating units – a geothermal heat exchanger and a heat-pump unit – using geothermal energy, that is

$$Q(t) = Q_g(t) + Q_{HP}(t), \tag{3}$$

where $Q_g(t)$ is the fraction of the total thermal load of Q(t) provided by the geothermal heat exchanger, kW; $Q_g(t)$ is the fraction of the total thermal load Q(t) provided by the heat-pump unit, kW.

$$\begin{cases} t_g' - 5 < \tau_1(t) \le t_c - 5 \\ \tau_2(t) \le t_g' - 5 \end{cases}, \tag{4}$$

where t_c – the condensation temperature in the heat-pump unit, ºC; $\tau_2(t)$ – the temperature of the network water in the return pipeline, depending on the temperature of the outside air, ºC.

If $\tau_2(t)>t_g'-5$ under the above conditions, the heat supply system will be provided with heat energy only by heat-pump unit.

The consumption of thermal fluid during the combined work of the geothermal heat exchanger and the heat-pump unit can be found by the formula from the balance equations:

$$G_g(t) = \frac{G_n \cdot \left[t_g' - 5 - \tau_2(t)\right]}{t_g' - t_g''}, \tag{5}$$

where Gn – the flow of network water in the heating system, kg/s.

$$\begin{cases} \tau_1(t) > t_c - 5 \\ \tau_2(t) \le t_c - 5 \end{cases}, \tag{6}$$

then the partial heating of the network heat carrier of the heat supply system to the condensation temperature, taking into account the not full recovery, can occur in the heat-pump unit, and the heating up to the required temperature in accordance with the temperature curve will take place in the boiler plant. Taking into account the feasibility study, it is possible to heat the heat carrier only in the boiler installation under these conditions.

If

$$\begin{cases} \tau_1(t) > t_c - 5 \\ \tau_2(t) > t_c - 5 \end{cases}, \tag{7}$$

then the heating of the heat carrier of the heat supply system is possible only in the boiler plant.

In general, the working conditions of all heat-generating elements of the hybrid fuel and geothermal heat station will depend on the specific values of the temperature curve of the heat supply system, the thermal load, the climatic conditions of the construction area, the thermal water parameters (temperature at the wellhead of the production well, the flow rate), and others.

Taking into account the above mathematical model of the operation of the hybrid fuel and geothermal heat station, do consider its work during the heating period on the autonomous or decentralized heat supply system for the following output data:

- the area of construction: thermal water deposit in Dzhankoy, Crimea;
- the maximum thermal load: 1.0 MW (heating);
- the temperature of thermal water at the wellhead of the extraction well: 64 ºC;
- the thermal water temperature after the geothermal heat exchanger: 25 ºC;
- the maximum temperature of the heat-carrier in the heat pump plant: 70 ºC;
- the temperature curves of the heating system: 90-70 ºC (option 1), 70-50 ºC (option 2).

The required flow of thermal water to cover the heat load, partially or totally, by the geothermal heat exchanger for two options of the temperature curve is shown in Fig. 2, and the change in its thermal power, depending on the temperature of the outside air is shown in Fig. 3

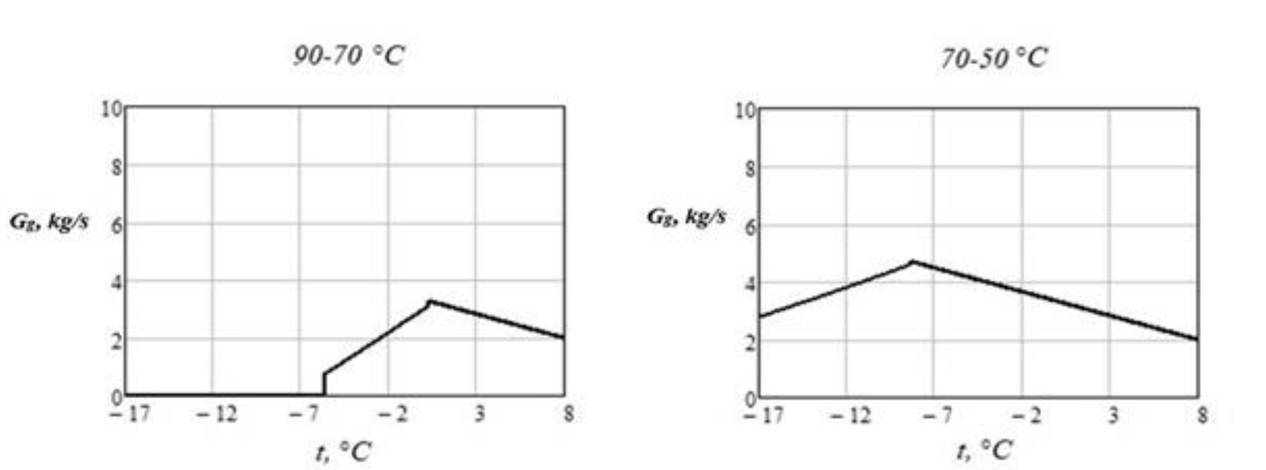

Figure 2: Graphs of the thermal water flow changing for provision of the partial or total coverage of the heat load by the geothermal heat exchanger, depending on the outside air temperature

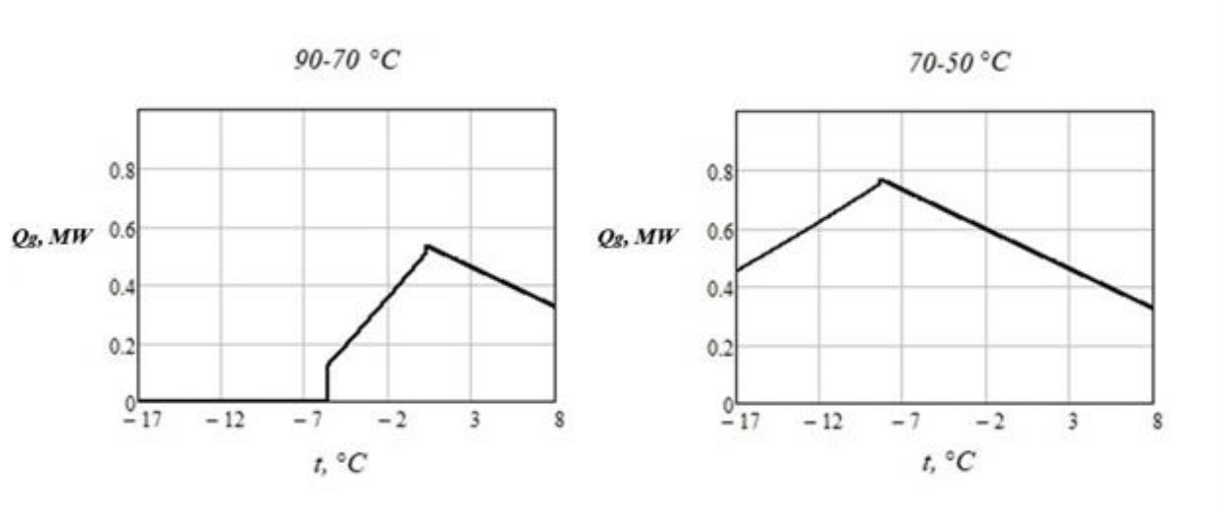

Figure 3: Graphs of thermal power change of a geothermal heat exchanger for provision of partial or total coverage of the thermal load, depending on the outside air temperature

Under the temperature curve of 90-70 ºC, the heat load coverage is provided by the geothermal heat exchanger to the outside air temperature +1 ºC, by the geothermal heat exchanger and the heat-pump unit – to -6 ºC. Under the temperature graph of 70-50 ºC, the coverage by geothermal heat exchanger is provided up to -8 ºC, by the geothermal heat exchanger and the heat-pump unit – to the outside air temperature, which corresponds to the calculated temperature for heating systems.

After the break point, with the decrease of the outside air temperature, the thermal water consumption decreases through the geothermal heat exchanger, because the thermal potential of the thermal water is not sufficient to obtain the heat carrier of the heating system with the specified parameters at the appropriate temperatures of the outside air. If necessary, the increasing in the consumption of thermal water through the evaporator of the heat-pump unit is possible by the parallel connection to the heating circuit of the hot water supply circuit or other heat consumption circuit using the heating water as a hot heat carrier for thermal water, or by additional supply of thermal water in parallel with the geothermal heat exchanger.

Graphically, the heat production capacity of the heat-pump unit for the partial coverage of the thermal load, depending on the outside air temperature is presented in Fig. 4

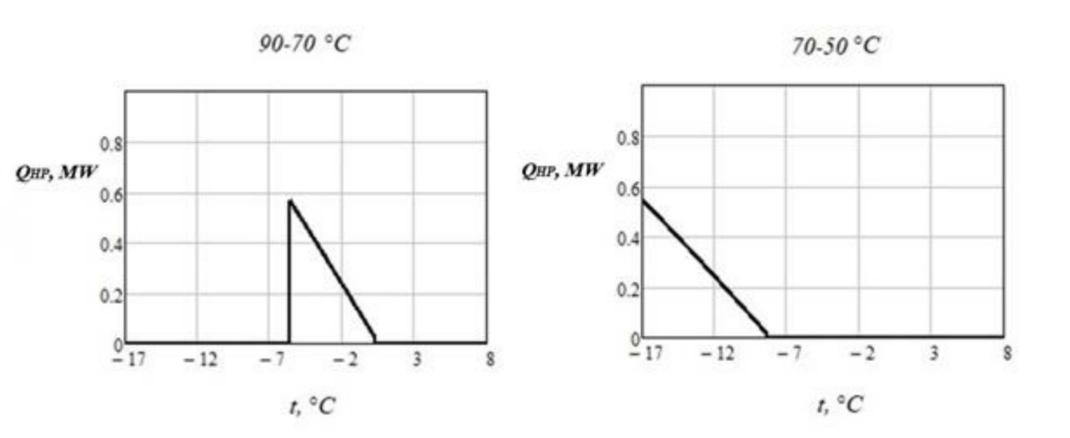

Figure 4: Graphs of the thermal power changing of the heat-pump plant to provide partial heat load coverage depending on the outside air temperature

In fig. 4 it can be seen that for a temperature curve of 70-50 ºC, the heat-pump unit is used for peak production from -8 ºC to -17 ºC, providing the necessary heat output with a geothermal heat exchanger without switching on the boiler plant (Fig. 5). Under the temperature curve 90-70 ºC, all three heat generating units operate. In this case, the heat-pump unit operates in a fairly narrow range of the outside air temperatures – from +1 ºC to -6 ºC. At lower temperatures only the boiler plant works, although this temperature range corresponds to slight duration of the heating period. To increase the duration of the heat-pump unit and to reduce using of the boiler plant, as well as its thermal power is possible due to the use of two-stage heat-pump units with the higher values of condensation temperature.

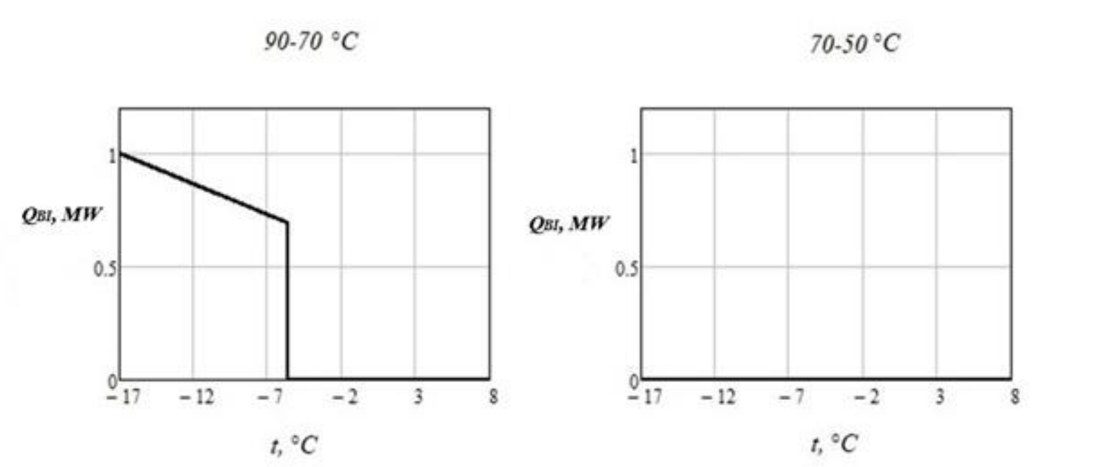

Figure 5: Graphs of changes in the heat capacity of the boiler plant to ensure the coverage of thermal load, depending on the outside air temperature

In the Fig. 6 graphs of heat consumption for the heating period for each temperature graph and the share of heat load coverage by each heat generating plant are shown. According to the temperature curve of 90-70 ºC, the geothermal heat exchanger covers 88.8% of the total heat consumption, 8.7% is covered by a heat-pump unit, 2.5% is covered by a boiler plant. According to the temperature curve of 70-50 ºC 98.5% of the total heat consumption is covered by the geothermal heat exchanger, 1.5% is covered by a heat-pump unit. A short period of exploitation of peak preheaters is due to the climatic conditions of the construction area. Consequently, for the given output data for two variants of the temperature curves, the overwhelming part of the thermal load is covered by the geothermal energy, providing relatively small consumption of fuel and electric energy for the drive of the heat pump plant. However, during the estimated lifetime of the operation, the share of the heat load of the boiler and heat-pump unit can increase due to decreasing in the flow of thermal water and decreasing in its temperature compared with the calculated ones.

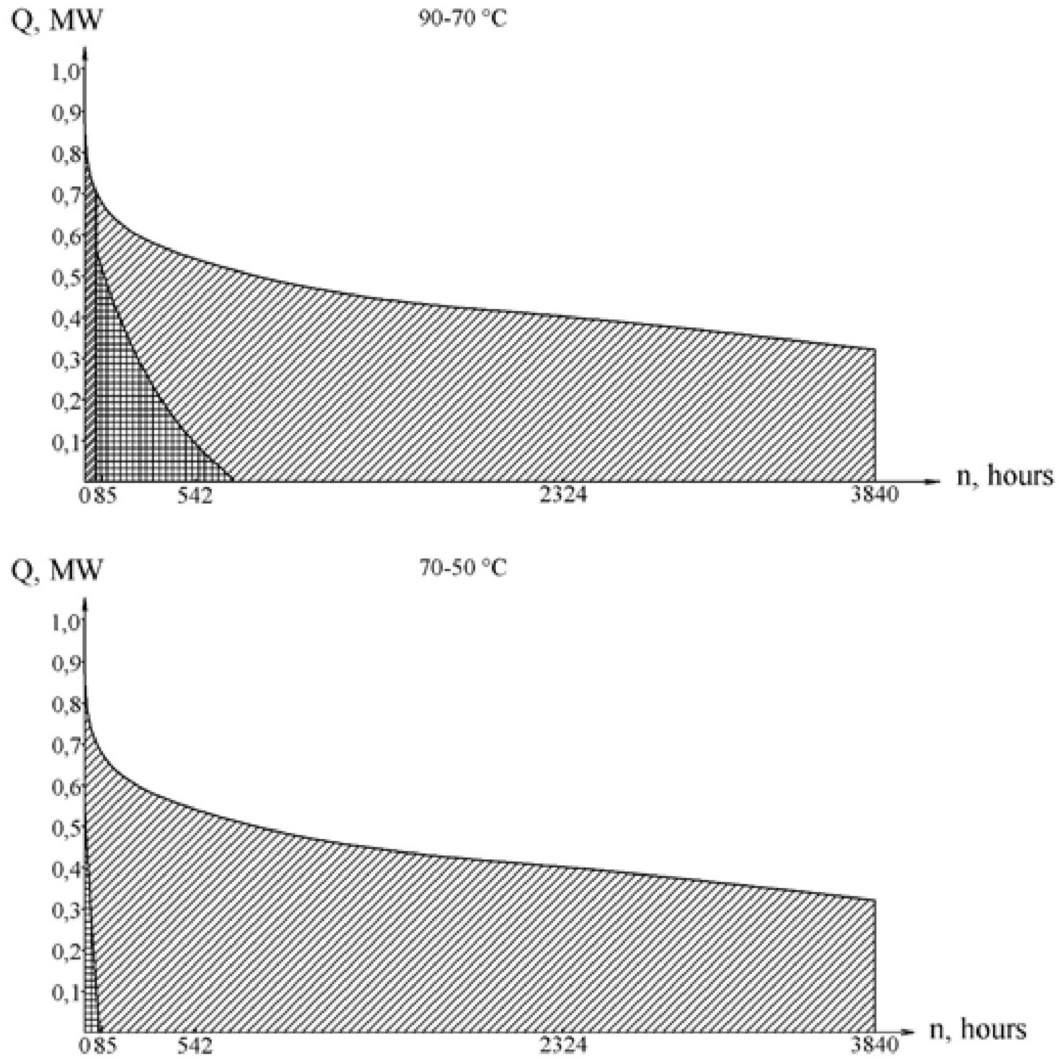

Figure 6: Graphs of heat consumption for the heat supply system from the hybrid heat station (inclined hatching – fraction of heat covered with geothermal energy in the geothermal heat exchanger; square hatching – fraction of heat covered by the geothermal heat-pump unit; inclined hatching with a double line – fraction of heat covered by the boiler plant).

Taking into account that various types of energy were involved in the operation of the hybrid heat station, the thermodynamic efficiency of the station was estimated by the exergy efficiency (Brodyanskiy,1991; DiPippo, 2008).

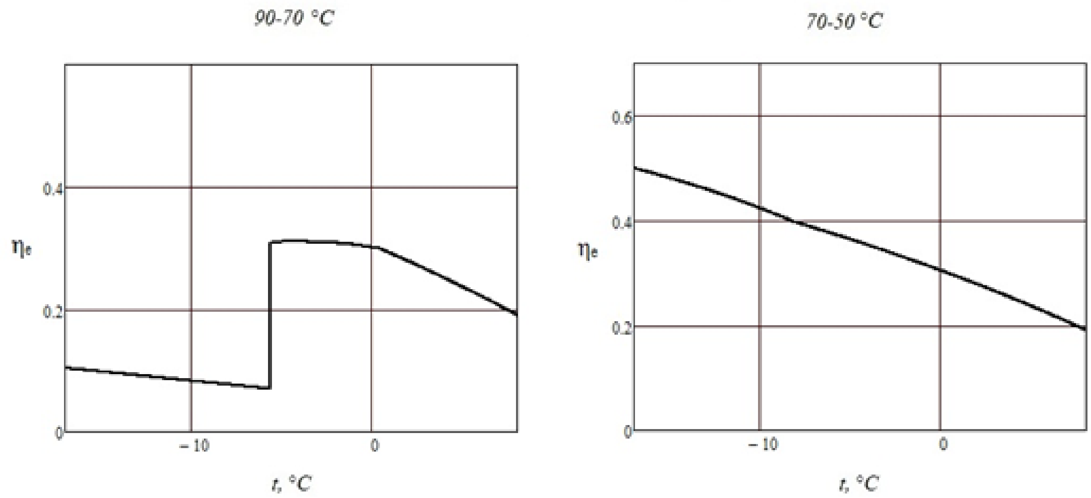

Figure 7: Graphs of changes of the exergy ratio of efficiency of the hybrid heat station, depending on the outside air temperature

Taking into account the duration of outdoor air temperature ranges during the heating period for the specified district of construction, the average exergy ratio for the heating period, for a temperature curve of 90-70 ºC is 21%, and for the option of 70-50 ºC is 27%. The maximum values of the exergy ratio at low air temperatures are achieving due to the reduced temperature curve by covering the overwhelming part of the thermal load with geothermal energy in a geothermal heat exchanger and a heat-pump unit, which also uses low-potential heat of thermal water.

CONCLUSIONS

The mathematical model of the operation of the hybrid heat station containing the geothermal circulation system, the heat-pump unit and the boiler plant. It allows to determine the technical parameters of the heat station, to predict heat supply regimes, to make comparisons of the options of heat supply regimes for taking of the rational choice.

In addition provision of the necessary heat production, the use of several heat sources within the station can increase the reliability of heat supply in the conditions of changing the parameters of the thermal fluid.

Increasing the energy efficiency of geothermal heat supply is ensured by the use of reduced temperature curves of the heat carrier of the heat supply system and utilization of the residual heat of a geothermal heat carrier by means of heat-pump units.

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