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INCREASING THE EFFICIENCY OF GROUND-SOURCE HEAT PUMPS BASED ON CONSUMER OPERATING MODE DATA

В. Шевчук, Ю. Рєпін, О. Паламарчук, О. Фуркаленко, С. Грищенко. **Підвищення ефективності експлуатації теплових насосів із відведенням теплоти від ґрунту на основі даних режимів експлуатації споживачів.** Впровадження відновлювальних джерел енергії в системи теплопостачання комунальної теплоенергетики відповідає сучасним політикам переходу на «зелену енергетику» та декарбонізації як промисловості так і різних галузей енергетики. В роботі проведено аналіз сучасних практик інтеграції теплових насосів автономних систем теплопостачання з відведенням теплоти від ґрунту, виявлені основні труднощі впровадження та експлуатації геотермальних теплонасосних систем. На основі проведеного аналізу визначено актуальний напрямок дослідження підвищення ефективності роботи автономних систем теплопостачання на базі геотермальних теплових насосів. Для проведення аналізу роботи систем теплопостачання обрано математичну модель, що дозволяє описати процеси теплозабезпечення споживачів різних видів за рахунок роботи системи теплопостачання на основі геотермальних теплових насосів та акумуляторів теплоти. Для окремого об’єкту проведено експериментальні дослідження роботи системи теплозабезпечення на основі теплового насосу за перший опалювальний сезон. На основі отриманих даних проведено узагальнення режимів роботи споживачів в залежності від періоду доби та температури навколишнього середовища. Доведено актуальність корегування режимів роботи теплонасосної установки на основі отриманих експериментальних даних за перший період експлуатації системи. Узагальненні данні роботи геотермальних теплових насосів дозволили запропонувати рішення підвищення енергоефективності системи теплопостачання та надійності роботи основних елементів системи генерації теплоти. Проведено математичне моделювання режимів роботи системи теплопостачання об’єкту на базі геотермальних теплових насосів впродовж доби з урахуванням наявних даних режимів роботи основних споживачів тепла. Запропоновано імпульсний режим генерації теплоти тепловими насосами. На основі отриманих результатів моделювання отримано діаграму роботи системи теплопостачання протягом доби. Для вирівнювання режимів роботи теплогенераторів запропоновано використання акумуляторів теплоти здатних зменшити максимальне розрахункове теплове навантаження теплових насосів у піки споживання, та забезпечення мінімальних потреб споживачів у спади теплових навантажень.
Ключові слова: геотермальні теплові насоси, системи теплопостачання, відновлювальні джерела енергії, акумулятори теплоти, режими теплоспоживання, теплогенератори

V. Shevchuk, Y. Riepin, O. Palamarchuk, O. Furkalenko, S. Gryshchenko. **Increasing the efficiency of ground-source heat pumps based on consumer operating mode data.** The introduction of renewable energy sources into the municipal heat power generation heat supply systems corresponds to modern policies of transition to "green energy" and decarbonization of both industry and various branches of power engineering. This study analyzes modern practices of heat pumps integration to autonomous heat supply systems with heat removal from the ground, identifying the main difficulties in geothermal heat pump systems implementation and operation. Based on the resulting analysis, a relevant direction of research on increasing the efficiency of autonomous heat supply systems based on geothermal heat pumps has been identified. To analyze the heat supply systems operation, a mathematical model has been selected that allows describing the processes of heat supply of various types of consumers with reference to the operation of a heat supply system based on geothermal heat pumps and heat accumulators. Experimental studies of the operation of a heat supply system based on a heat pump for the first heating season were conducted for a separate facility. Based on the data obtained, a generalization of the consumers’ operating modes depending on the 24-hourly period sector and ambient temperature has been carried out. The relevance of adjusting the operating modes of the heat pump installation was proven based on the experimental data obtained for the first period of system operation. The generalized data on the geothermal heat pumps operation allowed us to propose a solution to increase the heat supply system energy efficiency and the reliability of the heat generation system main elements. Mathematical modelling of the heat supply system operating modes in the facility based on geothermal heat pumps during the day was carried out, taking into account the available data on the main heat consumers’ operating mode. A pulsed mode of heat generation by heat pumps was proposed. Based on the obtained simulation results, a diagram of the heat supply system operation during the day was obtained. To equalize the operating modes of heat generators, the use of heat accumulators capable of reducing the heat pumps’ maximum calculated heat load during consumption peaks and ensuring the minimum needs of consumers during heat load declines was proposed.
Keywords: geothermal heat pumps, heat supply systems, renewable energy sources, heat accumulators, heat consumption modes, heat generators

1. Introduction

The issues of increasing energy efficiency and reducing carbonization in the energy production and industry sectors as well as in the municipal energy sector remain acutely relevant [1]. At the level

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of regulatory documents both in the global scale and in Ukraine it is recommended to introduce renewable energy sources in modern energy supply systems. At the same time, there exists also a broad support for the introduction of "green energy" into heat supply systems [2].

One of the areas of these policies implementation refers to the use of geothermal heat pumps (GHPs) in autonomous energy supply systems. In Europe (especially in the North Europe countries), these policies have long been implemented in the field of municipal heat and power, in other countries the practice of using GHPs is gaining momentum [3]. In Ukraine also, already there exist municipal heat power segments where widespread implementation of GHPs is ongoing.

At the same time, there are significant prospects for using GHPs in the context of heat supply, energy efficiency and environmental sustainability decentralization. However, there are a number of pressing problems in geothermal heat pumps implementation and effective operation:

– traditional design is based on fixed capacity, without taking into account the real conditions of partial load, soil temperature or heat exchange in pipes;

– thermal imbalance presence in the soil;

– fluctuations in soil temperature caused by climate change, urbanization and thermal interaction between wells;

– uncertainty about the long-term effectiveness of geothermal heat pumps;

– high drilling costs;

– lack of in-situ investigations, market barriers, high import dependence and state support nuances that affect objective information of consumers and investors;

– popularity of alternative systems (systems with variable refrigerant flow with air as an energy source).

The above circumstances justify the relevance of research into the operation of geothermal heat pumps in both autonomous and combined heat supply systems.

2. Analysis of literary data and formulation of the problem

Many research works are devoted to the problems of increasing the efficiency of ground-source heat pumps [4, 5].

Efficiency quantitative assessment concerning GHPs with and without the integrated photovoltaic thermal panels (PVT) demonstrates [6] that in the long term perspective this technology contributes to the soil temperature stabilization, especially in compact well fields. PVT integration allows decreasing the wells length by up to 50% and the drilling rigs number by up to 50%, which in certain conditions reduces investment costs by 9…23%. Using GHPs with PVT is recommended for densely built-up and cold regions.

Based on the case study [7] of a system where heating load dominates, it was found that fluctuations in soil temperature affect the GHPs efficiency, however, when heat balance stable condition, this effect is insignificant. A decrease in soil temperature by more than 2°C can lead to the system's inability to meet thermal needs, which requires hybrid solutions.

As shown in the study [8], investment costs make 20…40% of the normalized heating cost for GHP, and the total costs significantly depend on the system capacity, tariffs and discount rate. An increase in the discount rate up to 10% augments the cost of heat for GHP by 2.1…2.6 times. The system scale and the features of use significantly affect the GHP efficiency. Thus, the results show that political support is key factor to increasing the economic attractiveness of GHP in Ukraine.

A significant increase in GHP efficiency is possible when the GS-VRF system with a buffer tank installed between the ground heat exchanger and water-cooled VRF systems [9]. This system provides for periodic control of the pump, which reduces its power by 38% compared to traditional systems. The simulation showed the system efficiency at low and medium heat loads. The total energy consumption decreased by 25% and 8% compared to the CWV (constant water volume) and VWV (variable water volume) control, respectively.

It should also be noted separately that the GHP use efficiency depends on the heat load of consumers and their operating modes during the 24-hours period. The above factors significantly affect the heat pumps calculated thermal power and their efficiency both during the day and during the year [10]. At the same time, buildings of different types of purpose have individual features of operating modes, usually correlated during operation in the first heating period. Based on the research results, additional recommendations can be given concerning the heat supply system operating modes.

3. The purpose and objectives of the research

This study main objective is to determine methods for increasing the efficiency of ground source heat pumps in autonomous heat supply systems.

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To achieve this goal, necessary is to resolve the following tasks:

– to analyze the current state of heat pumps energy-efficient use;

– to conduct experimental studies of the operation of ground source heat pumps;

– to simulate, departing from the data obtained, the heat supply system operation based on ground source heat pumps using heat accumulators.

4. Methods of conducting research and processing experimental data

The main characteristic of a heat pump with heat extraction from the ground is the coefficient of transformation:

$$\varepsilon_{HP} = Q_1 / L.$$

In this case, the compression work in the compressor is equal to the difference between the amount of heat removed at a high temperature level Q_1 in the HP condenser and the amount of heat supplied at a low temperature level Q_2 in the HP evaporator [11]:

$$L = Q_1 - Q_2. \quad (1)$$

During the irreversible cycle of heat pump operation, the transformation coefficient is:

$$\varepsilon_{HP} = \eta_c \times \varepsilon_c = \eta_c \frac{T_c}{T_c - T_e}, \quad (2)$$

where: η_c – efficiency of the equivalent Carnot cycle; ε_c – energy conversion coefficient of the equivalent Carnot cycle; T_c – temperature in the HP condenser, K; T_e – temperature in the HP evaporator, K.

For a heat pump with heat extraction from the ground, the amount of heat transferred from the ground to the intermediate coolant is important. This significantly depends on the soil temperature in the boundary layer of the ground heat exchanger and the ground heat regeneration time.

When operating a combined heat supply system where a heat pump is the main heat source and using heat accumulators, the thermal power supplied to consumers Q_{con} at any time t will be determined by three options for the system's operating modes, for which the method [12] can be used:

$$\begin{aligned} Q_{con1}(\tau) &= Q_{HP}(\tau); \\ Q_{con2}(\tau) &= Q_{HP+AC}(\tau); \\ Q_{con3}(\tau) &= Q_{AC}(\tau). \end{aligned} \quad (3)$$

The first mode of operation of the heat supply system for consumers takes place when the heat capacity of the consumers heat supply is within the heat pump maximum heat capacity. This mode of operation is characterized by the heat pump's operation exclusively to meet the consumers' needs.

The second mode of operation of the heat supply system for consumers is that when the heat capacity of the consumers heat supply is greater than the heat pump maximum heat capacity. This mode of operation is characterized by the heat pump's combined operation with heat accumulator to meet the needs of consumers [13].

The third mode of operation of the heat supply system for consumers takes place when the heat capacity of the consumers heat supply is significantly less than the heat pump maximum heat capacity. This mode of operation is characterized by the heat accumulator operation exclusively to meet the needs of consumers [14].

For a hotel complex with a total area of 700 m^2 located in western Ukraine, a study of the operation of a heat supply system based on a heat pump with heat extraction from the ground has been conducted. The heat supply system includes two heat pumps each of 25 kW thermal capacity, with vertical ground heat exchangers, which operate (Fig. 1, 2) during the heating period.

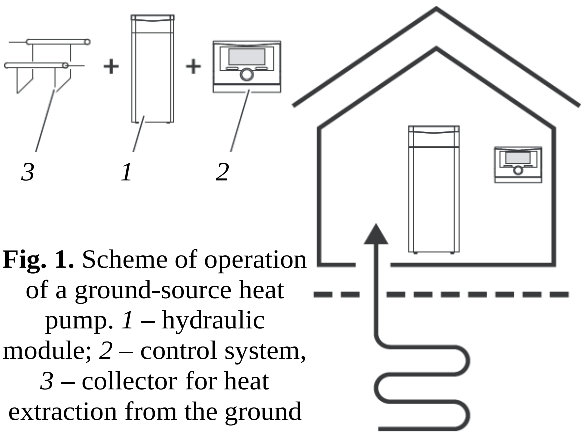

Fig. 1. Scheme of operation of a ground-source heat pump. *1* – hydraulic module; *2* – control system, *3* – collector for heat extraction from the ground

A ground-source heat pump is a vapor-compression refrigeration machine operating on the principle of the reverse Carnot cycle, taking into account various measures to increase efficiency (intermediate superheating/cooling, recovery, etc.). Water is used as heat carriers on the consumer side, and glycol mixtures are heat carriers on the ground heat exchanger side. The heat pump is a monoblock unit and is located in the technical rooms of heat generating systems. The collector connects the heat pump to a number of ground vertical heat exchangers.

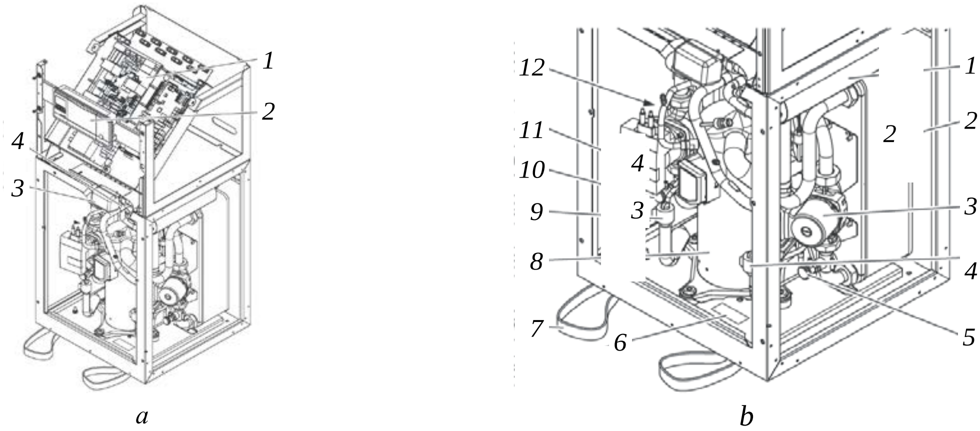

Fig. 2. Hydromodule internal arrangement for a ground-source heat pump: *a*) *1* – distribution box; *2* – control panel; *3* – heating / accumulator loading switch valve; *4* – 4-way valve; *b*) *1* – additional electric heating; *2* – condenser; *3* – heating circuit circulation pump; *4* – electronic expansion valve; *5* – filling and drain cock; *6* – nameplate; *7* – conveyor belts; *8* – compressor; *9* – electronic expansion valve; *10* – filling and drain cock of the circuit; *11* – circulation pump of the ground heat exchanger circuit; *12* – evaporator (ground heat exchanger not shown)

During the heating period (December 2024 – February 2025), observations were made of the main parameters of the heat supply system based on heat pumps, namely the thermal power generated by heat pumps was registered by type of heat supply (heating, hot water supply, DHW) (Fig. 3).

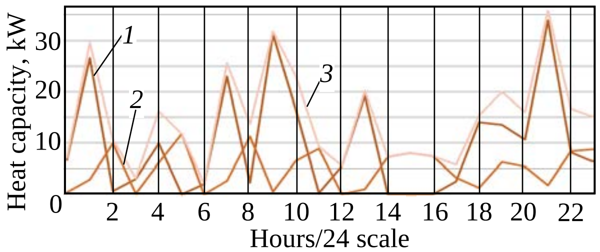

Fig. 3. Schedule of heat generation by the heat supply system during the 24 hours period, at an average outdoor air temperature during the day toutd = –8 °C: *1* – Heating heat generation, kWh; *2* – DHW heat generation, kWh; *3* – Total heat generation, kWh

The obtained data were summarized to determine operating load schedules targeting to identify the heat pumps' energy-efficient operating modes and ways to improve circuit solutions of the heat supply system.

As can be seen from the graph, the heat pump system operation has three clear main peaks of operation and two significant dips in heat consumption. Since heat pumps work according to the consumers' heat needs, this negatively affects the service life of the heat pump main elements primarily the compressor. Another factor that affects the efficiency of the HP is the share of the unit's power used when heat generation. It is known that each heat generator has its own limits of maximum and minimum permissible heat production power. When the heat power required for consumers decreases, the number of HP starts increases that also negatively affects the service life of heat pumps.

5. Results of experimental bench research

To solve the problem, it was proposed to transfer the heat supply system operation to a pulsed mode, taking into account the existing peaks and dips in operation during the 24 hours period (Fig. 4)

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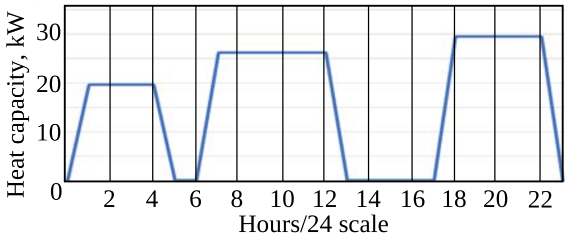

Fig. 4. Schedule of operation of a heat supply system based on heat pumps in pulse mode

The use of a pulse operation schedule divides the heat pump operation into two periods: working and non-working. During the working period, the heat load of the HP is constant during a specific peak. During the non-working period, the HP does not operate.

Analysis of the heat supply system operation schedule in pulse mode (Fig. 4) shows a more rational use of the HP operating resource due to its uniform operation in the heating period. It should also be noted that the maximum heat load is reduced from 36 kW to 30 kW, which additionally allows for a reduction in the heat generator maximum power.

However, there is a risk that the temperature in the rooms can fall below the minimum permissible, as well as the temperature of hot water delivered in the heat supply system non-working period.

At the same time, non-working periods represent a potential opportunity to use heat accumulators for ensuring the minimum needed during periods of dips in consumer heat loads, and further by reducing the maximum heat load due to heat accumulation.

To solve this issue, a simulation of the heat pump operation during the 24-hours period was carried out using heat accumulators and smoothing the peaks of the heat load of the heat pumps (Fig. 5).

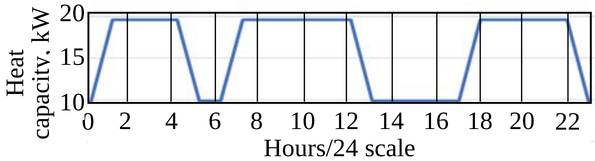

Fig. 5. Schedule of operation of a heat supply system based on heat pumps in pulse mode

Analysis of the graph (Fig. 5) shows a significant reduction in the maximum heat load on the heat supply system: 10 kW compared with the previous graph and 16 kW when compared with the current graph of heat load. The excess heat load is compensated by the operation of heat accumulators during the dips in consumer demand. At the same time, during the minimum heat demand periods, these needs are satisfied due to heat accumulation.

Further equalization of the heat load will lead to a significant increase in heat accumulators and a decrease in the rate of soil regeneration. The optimal value of the ratio between the maximum heat load reduction and the volume of heat accumulators requires additional research.

Conclusions

This research exposes the conducted study of geothermal heat pumps efficiency, taking into account both heating systems and hot water supply systems heat consumption modes as well as the features of the heat pump operation in autonomous heat supply systems.

In accordance with the tasks set, the following study stages were performed:

– analysis of the current state of heat supply systems based on geothermal heat pump systems and the relevant research topic identification;

– experimental studies of the heat pump system operation were conducted at a pilot facility (hotel complex) and a generalized schedule of the heat supply system operation during the 24-hours period was obtained;

– based on the experimental data obtained, there was proposed a pulsed mode of operation of the heat transfer heat supply system using heat accumulators;

– based on the mathematical simulation results, a graphical dependence of the geothermal heat pumps operation during the 24-hours period was obtained and the effectiveness of the heat accumulators use for smoothing the HP operation schedules and reducing the maximum calculated heat load of the heat supply system to 40%.

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