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# EXERGETIC CALCULATION OF THE EFFICIENCY OF HEAT PUMP INSTALLATIONS FOR A PRIVATE BUILDING

*Abstract*: The models and methods proposed in most of the works for evaluating the energy efficiency of ground-based heating systems for designers and implementers of heat supply systems for residential buildings are quite complex and highly specialized. Therefore, it is necessary to have a fairly simple and convenient in practical use mathematical model for assessing the energy efficiency of the heat pump installation for the selected scheme of geothermal heat supply. In this article, an exergetic calculation of the coefficient of the degree of thermodynamic perfection is proposed for choosing the appropriate the heat pump for the selected scheme and real operating conditions.

*Keywords*: low-potential heat of the soil, scheme of the heat pump installations «soil-water», exergy analysis, calculation of thermodynamic perfection of the heat pump.

## Introduction

Today, when humanity begins to realize that the problem of an ever-increasing shortage of non-renewable natural energy resources really exists, and their prices are constantly rising and will continue to rise in the future, the introduction of energy-saving technologies for the production of heat based on the use of non-traditional and renewable energy sources instead of burning hydrocarbon fuels is becoming less popular as it is vitally necessary. This is due, first of all, to the fact that an acute global problem is the ecological problem of preserving a healthy and comfortable human habitat. Thus, the introduction of heat pump installations (HPI) becomes a key task in the field of energy saving and ecology. In such developed countries as Austria, Germany, Switzerland, Sweden, Finland, the share of heat pump equipment in the total heating load reaches 30-50% [1-3]. From the point of view of stability and temperature level, the soil is the most acceptable source of low-potential heat, as it has a temperature of 8-12 ℃ at a depth of 4 *m* during the year in many countries of the world, which can ensure the energy efficiency of the HPI work [4].

## Analysis of the problem of using existing HPI

Despite the fact that at the moment important results have been obtained in a number of works, which facilitate the calculation and design of heat supply systems based on soil HPI, taking into account thermophysical processes occurring in the soil, at the same time there are problems that remain unsolved and require additional research [1,4-6]. The issue of accurate and effective assessment of the mutual influence of heat and moisture exchange in the soil on the productivity of geothermal ground thermal power plants remains unresolved. The patterns of complex thermodynamic processes occurring in the soil layers near the pipes of soil heat exchangers during repeated heating and cooling have not yet been elucidated. The influence of groundwater migration on the intensity of heat exchange between the soil and the pipes of soil heat exchangers has not yet been fully studied, which can be very significant, and as a result, heat exchangers cannot be used in those cases where it is necessary. make a long-term prediction of the effectiveness of soil heat collection systems, taking into account the initial data on the hydrogeology of the soils in the application area. It is also necessary to conduct further research on the energy analysis of the energy efficiency of heat exchange processes in the heat supply system when collecting low-potential soil heat during its long-term operation.

## Setting the problem

The use of HPI for geothermal heat supply requires, first of all, optimal architectural-planning, constructive and engineering-technological solutions of the building or structure as a whole, that is, the geothermal heat supply system must organically fit both into the building itself and into the surrounding area, as well as rationally connect them with other engineering systems [5-8]. Thus, in the practical implementation of geothermal heat supply systems for buildings and structures, the issue of choosing a scheme of the heat supply system based on the "soil-water" HPI and energy analysis of heat exchange processes is relevant. The models and methods for evaluating the energy efficiency of ground heating systems proposed in most works for designers and implementers of residential heating systems are quite complex and highly specialized. Therefore, it is necessary to develop a rather simple and convenient for practical use mathematical model of energy efficiency assessment of HPI for the selected scheme of geothermal heat supply.

## Solution of the problem

When vertical or horizontal registers of pipes (systems for collecting low-potential soil heat) are installed in the soil, thermal energy is extracted from the soil and transferred to the consumer. Fig. 1 and Fig. 2 show examples of vertical and horizontal low-potential soil heat collection systems. At the same time, the combined use of renewable heat sources is possible, as shown in Fig. 1.

With a horizontal system, the pipes of the soil heat exchanger are laid in earthen trenches 1.5-2 *m* deep, connecting the branches in series or in parallel. There are many configurations of vertical stacking of the heat exchanger, but here a large part of the costs falls on the drilling work. The length of the heat exchanger depends on its design (vertical, horizontal, etc.) and the performance of the heat pump. The design with the lowest installation costs is considered the best.

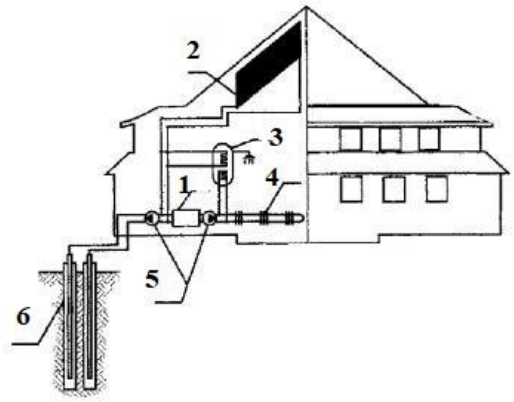


*Figure 1*. Scheme of heat supply of a residential building with a vertical system of collecting low-potential soil heat (1 – heat pump; 2 – solar collector; 3 – boiler for hot water supply; 4 – heating devices of the heating system; 5 – circulation pumps; 6 – vertical thermal wells of the system of collecting low-potential soil heat)

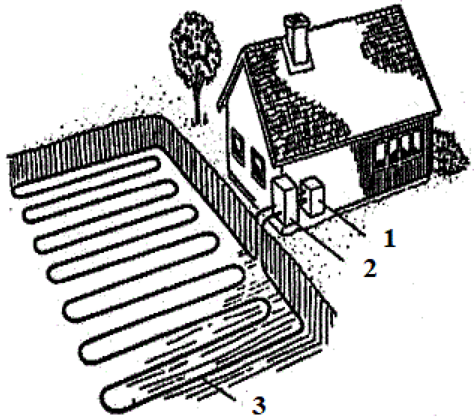


*Figure 2*. Scheme of heat supply of a residential building with a horizontal system for collecting low-potential soil heat (1 – air heating device; 2 – heat pump; 3 – plastic pipeline)

One of the main elements of the heat pump in the heat supply system is the heat pump (HP), which thermodynamically is a reverse refrigerating machine containing an evaporator, a condenser and a circuit that performs a thermodynamic cycle (Fig. 3) [9, 10].

The main types of thermodynamic cycles are absorption and the most common, vapor compression. Fig. 4 presents a schematic diagram of the operation of a compression TN [9, 10], where $Q_{cond}$ – heat removed from the condenser; $Q_{evap}$ – heat supplied to the evaporator; $L_{comp}$ – operation of the compressor.

Its principle of action is based on two physical phenomena:

– absorption and release of heat by a substance when the aggregate state changes (evaporation and condensation, respectively);

– a change in the temperature of evaporation (and condensation) with a change in pressure.

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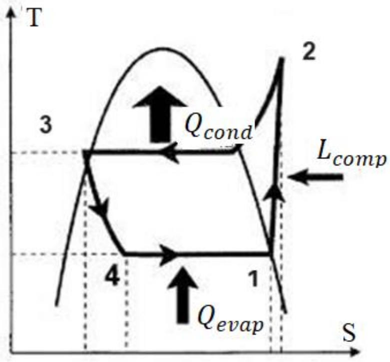


*Figure 3*. The thermodynamic cycle of the heat pump in the T-S diagram
(1-2 compression in the compressor; 2-3 removal of heat to the consumer;
3-4 expansion through the throttle; 4-1 supply of heat from a low-potential source)

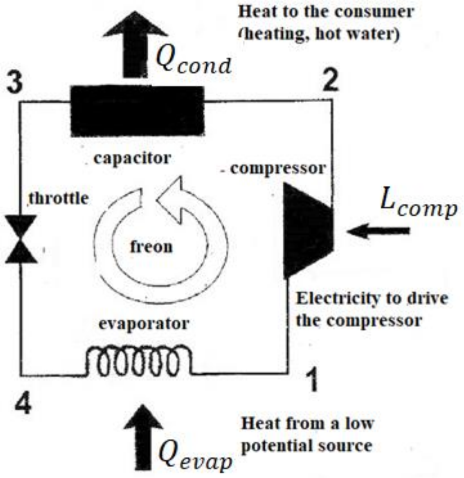


*Figure 4*. Schematic diagram of compression TN-operation

Depending on the combination of the type of low-potential heat source, HP are divided into the following types: *air - air; air - water; soil - air; soil - water; water - air; water is water*.

Regulation of the operation of heat supply systems using HP in most cases is carried out by turning it on and off according to the signals of the temperature sensor installed in the heat receiver. HP is usually adjusted by changing the cross-section of the throttle (thermoregulating valve – TRV).

The question of analyzing the energy efficiency of the selected construction of the HP is of great importance when using the HP. As already noted above, the models and methods proposed in most of the works for evaluating the energy efficiency of ground-level heating systems for designers and implementers of heat supply systems for residential buildings are quite complex and highly specialized. Therefore, it is necessary to have a fairly simple and convenient in practical use mathematical model for assessing the energy efficiency of HPI for the selected scheme of geothermal heat supply. This is primarily determined by the HP conversion factor both in terms of energy and cost.

The energy balance of the TN is written as follows:

$$Q_{cond} = Q_{evap} + L_{comp}. \tag{1}$$

The HP conversion factor is determined by the following formula:

$$\varphi = \frac{Q_{cond}}{L_{comp}} = \alpha \times T_{cond} / (T_{cond} - T_{evap}) \tag{2}$$

Fig. 5 shows the dependences of the ideal $\varphi_{id}$ and actual $\varphi_r$ (real) TN conversion coefficient on the refrigerant evaporation and condensation temperatures.

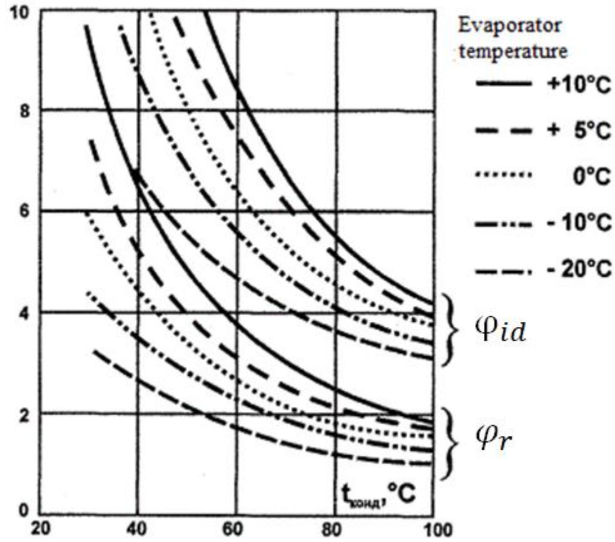


*Figure 5*. Dependence of the ideal and actual (real) TN conversion coefficient on the evaporation and condensation temperatures of the refrigerant

Using formulas (1) - (3) it is possible to choose HP relative to the given temperature regimes. There are two best-known methods of thermodynamic analysis to assess the energy efficiency of HPI: entropy and exergy. Entropy and exergy methods are built taking into account all the consequences of both principles of thermodynamics and use the abstraction of cycles to mathematically describe the degree of irreversibility of any real process, regardless of whether it is closed or open. The entropy method determines entropy growth and entropy-related losses only during throttling and irreversible heat transfer with a finite temperature difference. In all other cases, deviations from ideality are established empirically and are expressed by coefficients, the number of which is very large. Exergetic method of analysis is more complete for energy analysis of heat exchange processes in soil-water HPI [8-10]. Based on the method of exergy analysis of a real thermodynamic cycle, it is possible to determine not only the total exergy loss, but also the degree of thermodynamic


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perfection, as well as the conditions for dividing the total loss into fractions belonging to individual processes that make up the thermodynamic cycle.

Interaction of the system with the environment can be both reversible (ideal process) and irreversible (real process). In an ideal process, according to the definition of energy, the maximum work will be obtained, which is equal to exergy. In a real process, some of the energy will not be converted into work. This is one of the essential differences between exergy and energy. Exergy remains constant only in reverse processes. This basic property of exergy allows it to be used as a measure of the reversibility of one or another process.

The difference between the total amount of exergy supplied to this system $\boldsymbol{E_{in}}$ and the amount of exergy extracted from it $E_{ex}$ determines the total amount of losses of the real process, regardless of whether it is closed or open. from irreversibility in HP, i.e

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$$\sum_{i=1}^{n} B_i = E_{ent} - E_{exit}. \quad (4)$$

Or in other words, due to entropy, exergy losses caused by any irreversible process are equal to the product of the absolute temperature of the environment by the increase in entropy of all elements of the heat supply system:

$$\sum_{i=1}^{n} B_i = T_{env} \sum_{i=1}^{n} \Delta s_i, \quad (5)$$

where $\Delta s_i$ – entropy increase of the *i*-th element of the heat supply system; $T_{env}$ – temperature of the environment.

Formulas (4) and (5) give a general picture of energy costs. A more detailed analysis is provided below.

In HP, the working body is used in a reverse circular process, to which the necessary power $P_{rev}$ is supplied. The heat pump perceives the heat flow $(Q_{env})_{rev}$ from the environment and gives the heat flow $Q = (Q_{env})_{rev} + P_{rev}$ to the environment that is being heated. The heat flow $(Q_{env})_{rev}$, which is removed from the environment, is determined by the expression

$$(Q_{env})_{rev}, = B_Q = QT_{env}/T. \quad (6)$$

The $E_Q$ energy flow required for heating comes with a feed drive power

$$P_{rev} == \left(1 - E_Q \frac{T_{env}}{T}\right) Q. \quad (7)$$

At the same time, the heat flow $Q$ supplied to HP is the sum of $E_Q$ and $B_Q$ (Fig. 6*a*). HPI due to the exergy added as the necessary work takes heat from the environment, which is added to the environment that is heated at $T > T_{env} E_Q$. and $B_Q$ are determined by formulas (6) and (7).

Since real HPIs work irreversibly (Fig. 6*b*), to cover the loss of exergy flow in HPIs, additional drive power $P_{add}$ must be added [9]

$$P - P_{rev} = P - E_Q = P_{add}. \quad (8)$$

The flow of energy removed from the environment as heat will be less, i.e

$$Q_{env} = (Q_{env})_{rev} - P_{add} = B_Q - P_{add}. \qquad (9)$$

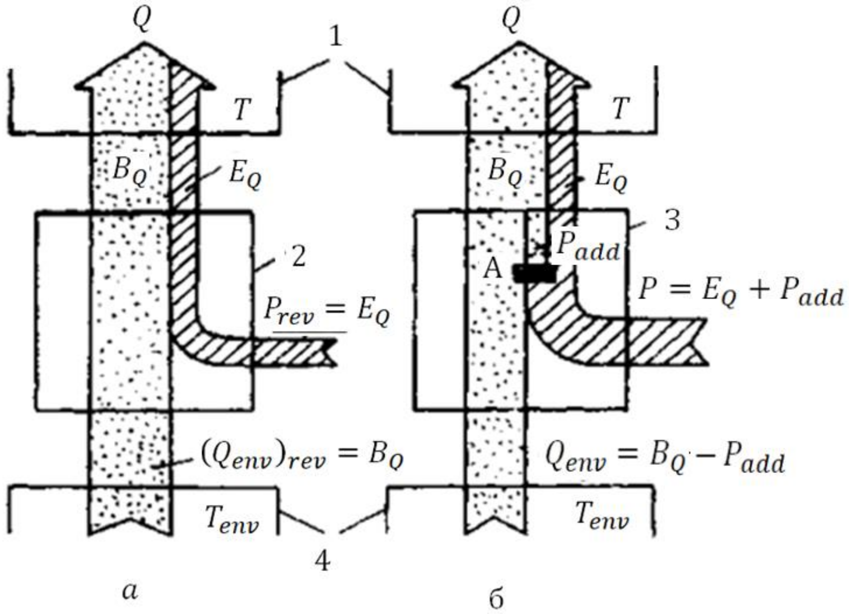


*Figure 6*. Flows of energy in TNU, working in reverse (a) and irreversible (b)
(1 – heated object; 2, 3 – reversible and irreversible heat pumps; 4 – environment)

The disadvantage of the methods based on the comparison and study of exergetic loss balances is the loss of connection with the reverse cycle. An already deformed irreversible cycle is taken for study. It is more appropriate to consider the actual cycle as a consequence of the transition: reverse cycle – theoretical cycle – actual cycle [9]. The following an irreversibility take place in compression HPs: internal (the compression process in the compressor and the throttling process); external (arising as a result of heat exchange at a finite temperature difference in the condenser and evaporator.

In the general case, the degree of perfection of HP in the heat supply system is defined as

$$\eta = \frac{E_q}{B_Q}, \qquad (10)$$

where $E_q, B_Q$ are determined according to formulas (6) and (8).

Thus, taking into account the real energy parameters of HP and the entire heat supply system of buildings will ensure the best energy efficiency of heat supply during the design and use of the «soil-water» heat supply system.

It should be noted that according to the results of work [8], the largest share of the cost of the heat supply system based on HPI falls on the soil heat exchanger, which is 34% of the total cost. In addition, in the main elements of the heat supply system, the compressor has a maximum irreversibility of about 53% of the total system irreversibility. From an economic

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point of view, the temperature entering the evaporator, the type of refrigerant and the climatic region have a large effect on the annual total costs that should be taken into account.

In addition, the practical implementation of the principle scheme of the geothermal heat supply system should be carried out taking into account the climatic features and the structure of the fuel and energy complex of the region, the energy level of natural and secondary low-potential heat sources, the requirements for the parameters of the heat carrier consumption and production systems, and the features of the required microclimate that is being served.

## Conclusion

When heating residential buildings with the use of energy-saving technologies, including the use of heat pumps that use the heat of secondary energy resources and non-traditional energy sources, it is necessary to consider the objects of heat supply as a single entity. It is necessary to achieve consistency of technical solutions regarding architecture, construction and engineering systems in order to choose the optimal schemes for implementing energy-saving technologies that ensure minimum payback periods for additional capital costs. Geothermal heat supply systems are implemented for a specific building or structure depending on energy loads, soil and climatic conditions of the area, their location and the cost of energy carriers. In particular, the problem of choosing the installed heat capacity of the heat supply system can be solved on the basis of the above energy analysis of TNU. In addition, an important element of the building's heat supply system is the ground heat exchanger. To choose an effective scheme for collecting low-potential soil energy, it is necessary to know the coefficient of thermal conductivity of the soil near the building, which is not always known a priori. In [14], a method of experimental determination of the coefficient of thermal conductivity of the soil in the zone of low-potential energy collection is proposed.

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