Combined heat supply “heat pump-solar plant” system

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Abstract. The article presents the possibility of a widespread introduction of heating systems using a heat pump, as well as a solar plant. Particular attention is paid to the useful properties of the combined heating. There are some assumptions in the mathematical model that do not affect the final result. The factors influencing the operating mode of the combined heating and hot water supply system are presented. It is indicated that the temperature of the condenser and the temperature difference have a significant effect on the combined heating system “heat pump-solar plant”. Thus, the joint operation of a heat pump and a solar plant will make it possible to rationally build a heating system.

1. Introduction

As practice and analysis of published works show, energy-efficient and resource-saving technologies began to dominate in the world. The improvement and development of technologies based on renewable energy sources significantly improve the coverage of required energy, which ultimately allows you to reduce fossil fuels, the release of harmful substances into the atmosphere, as well as provide the necessary energy resources to remote consumers. At the moment, systems built using heat pumps are acting as an alternative to traditional heating systems. This technology and its devices make it possible to generate heat for heating, hot water for consumer needs, and cold for the cooling and air conditioning system. In many countries, including Sweden, China, Russia, Japan, USA, Germany, Austria, there are a sufficient number of implemented systems based on a heat pump, but at the same time, the task of increasing the efficiency of these systems is still of interest \cite{1}. One of the options for increasing the heat supply system using heat pumps is also the additional connection of another source of renewable energy, for example, the sun. Sharing the energies of the Sun and the Earth will greatly enhance the heating system. Combination of a solar system with a heat pump, i.e. the formation of a single combined heat pump-solar plant system (CHPSPS) is possible in various variants of combined connection schemes. Eslami-nejad et al. \cite{2} in their work set the task in determining a rational configuration, so the technology with a single and several wells was studied; in option (a), the parallel operation of a heat pump and a solar collector was studied to generate hot water, and in option (b) the parallel operation of a heat pump and a gas turbine generator intended for heating a building. The authors explored the possibilities of channeling excess solar energy into the well. It was found that when using one well, the efficiency of the heat pump increases slightly, but when operating the system with two or more wells, the efficiency of the system increases significantly. Kjellsson et al. \cite{3} in their work considered the possibilities of various combinations of connection schemes for a solar collector and a heat pump.
authors have proven that the optimal connection scheme is a system in which solar energy is used in summer to generate hot water, and in winter to generate heat for pumping into a well. Hawlader et al. [4] carried out in-depth studies of the combined use of the energies of the Earth and the Sun. In this work of the authors, the solar installation is also intended as an evaporator for a heat pump. The authors found that solar radiation is the main factor affecting the thermal characteristics of the system; manifold usable space and storage size are also significant factors.

Khallyev et al. [5], presented the results of comparison and variation of various solar installations and heat pumps are presented. This result allowed the author to recommend the main parameters and characteristics of the combined system. In the article, the calculated data determined the required surface of the solar installation to provide a given power. Shown as the angle of incidence of sunlight and the level of insolation affects the production of hot water. The authors have shown that the efficiency of the combined system is 2 or more times higher than traditional or separate heating and hot water supply systems. The authors [6] of investigate the issues of temperature characteristics of a combined technology based on a heat pump and a solar water heating installation. The analytical form shows the energy balance of the HPSP system. Formulas for evaluating the thermodynamic parameters of the noted technology are given. In addition, a literature review of works on thermodynamic analysis of the HPSP system was made. Indicators and parameters of connection diagrams for heat pumps and solar installations are also given. The main problems of the schemes of combined connection of the HPSP system are shown, the tasks to be solved in the future are indicated. In conclusion, according to the authors, the combined system HPSP is a promising technology for use in heating and hot water supply technologies. In [7], the authors studied a combination of schemes for connecting a heat pump and a solar plant for heating and hot water supply. The authors set the task to study the efficiency of the system with different heat sources: geothermal, solar and air. A comparative assessment of experimental data showed that when using a combined and combined heat supply system, the efficiency increases by 20% or more relative to a heat pump system in the "air-water" scheme. The combined system has an energy efficiency rating of more than 3, although this figure is not entirely high. In this work [8] is the best combination and connection diagram of various types of renewable energy sources. It is shown that the combined system HPSP possesses the best characteristics. Multi-criteria optimization was carried out: the minimum financial costs for the construction of the system, as well as the maximum amount of generated energy. It has been determined that the combined HPSP system will be able to meet the requirements and objectives of the optimal mode. The authors show that financial costs are up to 79,000 euros, and the energy demand is achieved within 28-30 kW/m². Thus, the recommended scheme and combination of different renewable energy sources can save money and provide sustainable energy.

In addition, recently, studies have been carried out to optimize the operating modes of the CHPSPS, taking into account many factors, for example, the cost of the installation, connection schemes, the environment and environmental safety. In these works, the optimization is based on artificial intelligence technologies. Thus, the authors in their work [9] revealed the possibilities of artificial intelligence based on a genetic algorithm and neural networks in the optimization of the CHPSPS. The authors have shown the possibility of effectively reducing financial costs. The genetic algorithm technology made it possible to build a rational structure of neural networks, and the neural networks themselves were designed to predict the generated energy depending on the conditions. Also, researchers have developed mathematical models of CHPSPSs. Thus, in [10], a mathematical model of the CHPSPS was compiled. The results of simulation modeling of the created model showed that there is a unique opportunity to build a heat supply system based on the CHPSPS, which under various climatic conditions will provide an efficiency close to 5. At the same time, in the article [11], the authors propose a mathematical model of the CHPSPSs. This model allows you to determine the ratio of the input and output power of the heat pump. In the proposed system, the efficiency reached 3, which is significant for the selected region - China.
2. Method
As the experience of work and the implementation of developments show, today heat pumps built according to the air-to-air system are widely used. From a financial point of view, this technology is the most economical since the initial cost is the lowest. But at the same time, due to the instability of the external environment, maintenance costs are becoming high. To ensure stability, a constant input parameter is required, which corresponds to the ground temperature. In contrast to the air-to-air system, the cost of introducing a geothermal heat pump is higher, but since the ground temperature is stable, it reduces operating costs. Figure 1 shows the combined system "solar collector - solar plant". In this system, the incoming flows are the energy of the Earth and the Sun, which are converted by heat exchangers and a solar plant. The schematic diagram in a simplified form of the combined heat supply CHPSPS is shown in figure 2.

![Diagram](image)

**Figure 1.** Energy flows of the Earth and the Sun for the "thermal pump-solar plant" system.

Experience shows that it is very difficult to scientifically substantiate the effectiveness of a system without creating a dynamic model of the object. It is of scientific interest to study thermodynamic and hydrodynamic phenomena in a structurally complex technology, which consists of several objects, such as: a heat pump, a solar plant, several recuperative heat exchangers, transfer pumps, and coolant accumulators.

This judgment is confirmed by the presence of a large number of internal feedbacks between the parameters characterizing the technical state of the system to ensure a given heat load. In addition, in the CHPSPS there are constant changes in the level of disturbing influences, such as heat accumulation, solar radiation, heat load and others. These factors explain the difficulty of obtaining a satisfactory static solution. In addition, the combined CHPSPS contains modern controllers that regulate a specific parameter and thus affect the state of the system as a whole.

There are two known methods for establishing the dynamic characteristics of the CHPSPS. In the first method, experimental studies of the CHPSPS are carried out, and then, based on the results of the experimental data, a model is created using the input and output parameters. The second method involves the calculation path, that is, the construction of a mathematical model of the CHPSPS, taking into account all influencing factors: design parameters, technological characteristics of the installation, laws of physics, and so on. Experimental identification of dynamic characteristics is possible if there is a working CHPSPS. In this case, as a rule, it is impossible to get a complete picture of the internal structure of the object or the existing internal relationships of parameters, as well as to establish how the dynamic characteristics can affect the choice of the optimal configuration.
2.1. Problem formulation

Simulation of a solar plant. In this context, we will investigate and formulate some characteristics of the CHPSP. When creating the model, the following assumptions and replacements were made: the collector was replaced with a pipe with a radius R, the soil around the collector was replaced with a cylinder with a height L, and its inner hole with a radius r. This model, built according to the CHPSPS, allows you to find the influence of the main (external and internal) factors on the operating mode of the heat supply system. Further, it will be determined how the temperature of the working fluid will be distributed in the volume of the pipe. The field temperature inside the heat exchanger is found by the formula:

\[
(1 - r^2) \frac{\partial \Theta_i}{\partial \hat{x}} = Pe^{-1} \cdot \frac{L_0}{R} \cdot \frac{1}{r} \cdot \frac{\partial \Theta_i}{\partial r} \hat{r},
\]

where \( \hat{x} = x/L_0 \) - dimensionless coordinate along the axis of the heat exchanger; \( x \) - depth, m; \( \hat{r} = r/R \) - dimensionless radius; \( r \) - is the distance of the collector tube axis to a point in the pipe or soil at a given depth, m; \( \Theta_i \) - dimensionless value of the working fluid, which is determined according by

\[
\Theta_i = \frac{T_i(x,r) - (T_0 - \Delta T)}{\Delta T},
\]

here \( T_i(x,r) \) temperature of the working fluid at a point with coordinates \((x, r)\), and, moreover, \( r < R \) or \( r < 1, ^\circ\text{C} \); \( Pe \) - Peclet number, which is determined according to the formula:

\[
Pe = \frac{V_x R}{a_l},
\]

here \( a_l = \frac{\lambda_l}{c_p \rho_l} \) - thermal conductivity coefficient of the working fluid, m²/ s; \( V_x \) - fluid flow velocity in the cross section of the heat exchanger tube at a distance \( r \) from the tube axis, m / s, is determined by the well-known Stokes formula

\[
V_x = \frac{\Delta p}{4 \mu 2L_0} (R^2 - r^2),
\]
where \( L_0 \) is the degree of temperature fluctuations in the context of a season or cycle, that is, the maximum mark at which fluctuations in the ground even with changes in the ambient temperature.

The mode of operation of the solar collector is described by an equation in which the energy of solar radiation characterizes the ratio of useful energy and loss. Thus, the useful power obtained from the solar plant is the ratio of the amount of solar energy absorbed by the collector and the amount of energy lost to the environment:

\[
Q_u = F_R A[I_T(\overline{\alpha}) - U_L(t_1 - t_2)],
\]

where \( Q_u \) is the useful energy removed from the collector per unit of time, W; \( A \) - collector area, m\(^2\); \( F_R \) is the coefficient associated with the efficiency of heat transfer from the collector plate to the heat removal fluid; \( I_T \) is the total solar radiation flux density per unit area of the collector surface, W/m\(^2\); \( \overline{\alpha} \) is reduced absorption capacity, taking into account the resulting effect of the optical properties of the collector materials; \( U_L \) is the total heat loss coefficient of the collector, W/(m\(^2\)°C); \( t_1 \) is the temperature of the liquid at the inlet to the collector, °C; \( t_2 \) - ambient temperature, °C.

**Heat pump simulation.** The technological regime in the soil layers is characterized by: the ratio of the heat transfer of the working fluid in the pipes and the heat loss to the environment. In this case, we will use the heat conduction equation, which characterizes the process under study to the required extent:

\[
\left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right) + \frac{q_r}{\lambda} = \frac{1}{a} \frac{\partial T}{\partial t},
\]

where \( q_r \) is heat source member, W/m\(^3\); \( \lambda \) - soil conductivity coefficient, W/mK; \( T \) is temperature in the soil; \( x, y \) and \( z \) are space variables.

The heat transfer coefficient for ground heat transfer \( (U_g) \) is determined according to the equation [12]

\[
U_g = 0.999 \left( \frac{k_g}{d_g - d_p} \right) + 1.37 \left( \frac{k_g d_p}{A_p} \right),
\]

where \( k_g \) is the thermal conductivity of the ground, \( d_g \) is the depth to the water table or the constant source/sink from the ground surface, \( d_p \) is the pond depth, and \( P_p \) is the pond perimeter. The conduction heat transfer between the ground and the pond is then given by

\[
q = U_g A_p (T_g - T_p),
\]

where \( A_p \) is pond area, m\(^2\); \( T_g \) is ground temperature °C; \( T_p \) is pond temperature °C.

According to [13] the heat pump can be represented as two sections of a continuous flow heat exchanger, separated by a wall with internal intercooling and simultaneous heating. The heat transferred from the cold section \( Q \), and the heat transferred to the heated medium \( Q_s \) are related to the power to drive the compressor \( P_m \) of the heat pump, by the equation. The heat balance equation for heat fluxes in a heat pump by

\[
M_X C_B (t_{x2} - t_{x1}) - Q_X = m_{rx} C_B \frac{dt_{x1}}{dt},
\]

\[
Q_g + M_H C_B (t_{n2} - t_{n1}) = m_{TH} C_B \frac{dt_{n2}}{dt}.
\]

The power to drive the compressor of the heat pump is variable, and the transformation ratio of the heat pump will change due to changes in temperatures in the condenser and evaporator.

**3. Results and discussions**

The presented mathematical description of the CHPSPS makes it possible to build an energy diagram and power balance. This will make it possible to qualitatively and without deep calculations determine the operating mode of the CHPSPS. Minor simplifications of the equations of the CHPSPS allow you to build a picture of the consumption and production of thermal energy. These equations have the ability to take into account the modes of operation of both individual units and the entire system under study.
as a whole. The analysis of the results shows that the operating mode of the CHPSPS providing maximum heat production while reducing operating costs is the most acceptable technical solution.

4. Conclusions
The analysis of the work results showed that the combined use of the CHPSPS makes it possible to build a rational heating and hot water supply system. A number of assumptions are made in the equations for the solar plant, including: replacement of collector, soil and internal diameter. With these assumptions, it is possible to investigate the properties of the CHPSPS. Optimization of the dimensions and parameters of the CHPSPS allows increasing the technical and economic performance of the entire system as a whole.

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