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Simulation of Hybrid Solar Collector Operation in Heat Supply System

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Abstract

The paper focuses on the investigation and the simulation of the efficiency of a hybrid solar collector in a heat supply system consisting of two separate units, namely a heat storage tank and a flat solar collector, which are interconnected by pipelines. The study includes the analysis and calculation of the thermal parameters of the system for one day and the determination of the optimal values of the flow rate of the heat carrier in the solar collector and the mass of the heat carrier in the heat storage tank to achieve maximum thermal efficiency of the system. The authors use SolidWorks software and additional scripts programmed using Python to simulate the operation of the solar collector and to calculate its thermal efficiency. The results of the study show the high potential of hybrid solar collectors for efficient generation and accumulation of thermal energy both for households and small industries. This paper may be useful for engineers and scientists working in the field of alternative energy sources and energy-efficient systems.

Keywords: hybrid solar collector; heat supply system; heat storage tank; simulation.

1. Definition of the problem to be solved

Considering the environmental problems that have become particularly acute in our time, the world scientific community, as one of the ways to resolve the Paris Agreement, proposes to significantly increase the production of energy from RES, gradually replacing traditional carbon-based fuels. In this process, special attention is paid to the development of solar energy, the amount of energy from which has increased significantly over the past decades and, according to European energy and climate plans, its further increase is predicted to double on average by 2030 [1]–[3].

It is a well-known fact that the sun emits a huge amount of energy. According to approximate estimates of authoritative international organizations, the amount of solar energy received by our planet exceeds the annual energy consumption of the world's population by 27.000 times. The annual flow of solar radiation per 1 m^2 of a surface in the southern regions of Ukraine reaches 1350 kW/m^2. The volume of solar energy is practically not exhausted, so this amount of energy will be enough for us for hundreds and even thousands of years to come. Therefore, the issue of the rational use of solar energy and its effective transformation into electrical or thermal energy using special solar facilities is relevant [3], [4].

2. Analysis of the recent publications and research works on the problem

Nowadays, solar energy is widely used in housing, hotels, commercials, and small food and processing industries for generating both electric and thermal energy [4]–[6]. Lots of researchers investigate new technologies of solar energy [4]–[16] and develop new highly energy-efficient materials for covering solar panels [17], [18].

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The most common types of solar collectors are flat plate solar collectors, evacuated-tube solar collectors, and hybrid photovoltaic-thermal solar collector systems. They differ in design and efficiency as well as testing methods that are analyzed in [7]. In comparison, flat plate solar collectors have a low heat transfer rate owing to the low convective heat transfer coefficient between the working fluid and the absorber surface. Their performance can be increased by increasing the heat transfer area, employing a material with high thermal conductivity, extending the travel time of air, inducing turbulence, and altering fluid motion [7], [8]. Evaluation and optimization of the performance and efficiency of a hybrid flat plate solar collector integrated with phase change material and heat sink is carried out in [16]. The results demonstrated that such collectors equipped with a phase change material and heat sink produced hot water for a longer period in the evening while having a lower output temperature in the morning.

Paper [9] presents a review of thermal energy storage system design methodologies and the factors to be considered at different hierarchical levels for concentrating solar power plants. Thermal and exergy efficiency are analyzed for various thermal energy storage systems integrated into the power plant. In [10], the authors carried out transient analysis and techno-economic assessment of thermal energy storage integrated with solar air heater for energy management in drying. Paper [11] contains a review of sensible heat-based packed bed solar thermal energy storage system for low-temperature applications.

Many researchers are focused on using solar energy to obtain thermal energy for heat supply systems. The efficiency of the solar roof in the gravity system of heat supply is determined in [12]. The authors proposed new constructions of solar collectors in which the top cover of the solar collector is made of corrugated roofing material of the building. This design of the solar collector will make it possible to reduce its cost significantly and increase its durability. Theoretical and experimental analysis of solar enclosure as part of energy-efficient houses is made in [13]. An analysis of the energy indicators of the combined heat supply system using a solar window as part of the enclosure of an energy-efficient house was carried out. To improve the efficiency of the investigated setup, the stratification of the heat carrier in the heat storage tank of the combined heat supply system with a solar window was calculated.

Considerable attention is also paid to the issue of increasing the energy efficiency of solar collectors [4], [8], [14]–[16]. The solar photovoltaic panel's efficiency is significantly diminished by an increase in operating temperature. To solve this problem, different types of panels were investigated and experimental analysis of solar panel efficiency improvement with composite phase change materials was carried out in [14]. The efficiency of different solar collectors, particularly multi-pass solar air thermal collector systems assisted with a sensible energy-storing matrix is experimentally studied in [15]. The new more robust and repeatable methodology to assess the optical efficiency of a solar collector is presented in [16]. The transient heating of the empty collector is proposed as an indicator to deduce its optical efficiency, thus avoiding measuring the fluid temperature increase.

The energy sector of leading countries often uses hybrid photovoltaic-thermal solar systems to obtain both thermal and electrical energy. In this case, energy is traditionally generated by two separate systems consisting of thermal solar collectors and photovoltaic panels, respectively. Photovoltaic technology solar energy converts into electricity, and thermal solar technology converts solar energy into heat. Such a hybrid system is operated solely by solar radiation. However, despite their advantages, the applicability of photovoltaic-thermal solar systems is limited due to some drawbacks such as non-uniform cooling, low efficiency, high cost, not suitable to integrate with present roof systems, and need for larger space for separate systems [19], [20].

To reduce the influence of the indicated shortcomings and increase the efficiency of the operation of the photovoltaic-thermal collector, the authors proposed to perform a computer simulation of the system with such a solar collector. The investigated installation is a photovoltaic-thermal collector with solar cells glued directly onto the absorber plate. It allows one to receive simultaneously thermal and electrical energy, which is undoubtedly cheaper than two separate systems for each type of solar energy [21], [22].

3. Formulation of the goal of the paper

To achieve the goals set in the energy plans of developed countries, the intensification of the use of alternative energy sources is one of the important tasks. The use of such systems requires improvement and investigation of the new solar energy installations for generating thermal and electrical energy – hybrid solar collectors. Therefore, the purpose of this paper is to investigate the operation of the hybrid solar collector in the heat supply system and determine the optimal values of the mass flow rate of the heat carrier in the solar collector and the mass of the heat carrier in the storage tank to achieve its maximum thermal efficiency for the given conditions.

4. Theoretical prerequisites

In this paper, we consider the operation of the heat supply system with a hybrid solar collector with forced circulation of the heat carrier, which is shown in Fig. 1 [21], [22].

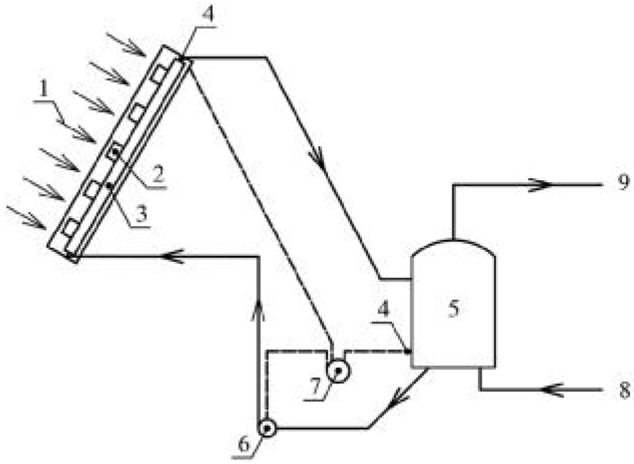

Fig. 1. Schematic diagram of the heat supply system with a hybrid solar collector: 1 – solar radiation; 2 – photocell; 3 – solar energy absorber; 4 – temperature sensor; 5 – heat storage tank; 6 – circulation pump; 7 – differential thermostat; 8 –return line of the cooled heat carrier in the consumer circuit; 9 – supply line of the hot heat carrier in the consumer circuit.

The system consists of a heat storage tank (HST) and a hybrid flat solar collector for obtaining thermal and electrical energy, interconnected by pipelines through which the heat carrier (water) moves with the help of a circulation pump. To simplify the calculation of the parameters of heat supply system, it is assumed that these pipelines are well insulated, so solar energy is absorbed only by the hybrid solar collector. Part of the received solar energy is used to heat water in the installation circuit and the rest is lost, including in HST. The water temperature at the entrance to the solar collector is taken equal to the average water temperature in the HST, and the water temperature at the entrance to the HST is taken to be equal to the water temperature at the outlet from the collector.

Useful thermal energy, which is accumulated by water in a thermal solar collector and is removed from it per unit of time Q_u, W is determined from the heat balance equation by the formula [21], [22]:

$$Q_u = F_R \cdot A_C \cdot [I \cdot \tau \cdot \alpha - U_L \cdot (T_S - T_a)], \quad (1)$$

where F_R is the coefficient of heat removal from the solar collector; A_C is the solar collector area, m^2; I is the intensity of solar radiation perceived by the surface of the solar collector, W/m^2; τ is the coefficient of transmission of solar energy through the transparent protective coating of the solar installation; α is the coefficient of absorption of solar energy by the absorber; U_L is the coefficient of heat loss of the solar collector, W/(m^2·°C); T_S is the average water temperature in the heat storage tank, °C; T_a is the ambient air temperature, °C.

If the consumers do not take away the heat, the received thermal energy accumulated in the HST per unit of time is determined by the formula:

$$Q_u = M_S \cdot c_p \cdot \frac{dT_S}{dt} + U_S \cdot A_S \cdot (T_S - T_a), \quad (2)$$

where M_S is the mass of water in HST, kg; t is the time, s; U_S is the heat transfer coefficient of HST, W/(m·°C); A_S is the area of the HST side surface, m^2; dT_S/dt is the change in water temperature during the time interval dt.

The efficiency of the hybrid solar collector in generating thermal energy is equal to:

$$\eta_C = \frac{G \cdot c_p \cdot (T_{out} - T_{in})}{I \cdot A_C}, \quad (3)$$

where G is the mass flow rate of water in the heliosystem circuit, kg/s; c_p is the specific heat capacity of water at constant pressure, J/(kg·°C); T_{out} is the water temperature at the outlet of the solar collector, °C; T_{in} is the water temperature at the inlet to the solar collector, °C.

The differential equation of the thermal balance of the operation of the heat supply system, which consists of a hybrid solar collector, turned-on circulation pump, and a HST without consumers taking away heat energy has the below form:

$$F_R \cdot A_C \cdot \left[I \cdot \tau \cdot \alpha \cdot \left(1 - \eta_{pc} \cdot \frac{A_{pc}}{A_C}\right) - U_L \cdot \ (T_S - T_a) \right] = M_S \cdot c_p \cdot \frac{dT_S}{dt} + U_S \cdot A_S \cdot (T_S - T_a), \quad (4)$$

where η_{pc} is the efficiency of conversion of solar radiation falling on the surface of each photocell into electrical energy; A_{pc} is the total area of the front surface of the photocells glued on the thermal part of the hybrid solar collector, m^2; A_C is the total area of the solar collector, m^2.

The circulation pump is controlled using a differential thermostat, which compares the temperature of the heat carrier from two sensors: the first measures the heat carrier temperature at the outlet of the hybrid solar collector, and the second measures the heat carrier temperature at the outlet of the HST. In the absence of heat carrier circulation in the system, the average temperature of the absorber T_p is taken as equal to the average temperature of the stationary heat carrier in the collector T_{st}.

Thus, the differential equation of the heat balance for a hybrid solar collector in the presence of heat carrier circulation has the following form:

$$\tau \cdot \alpha \cdot I \cdot \left(1 - \eta_{pc} \cdot \frac{A_{pc}}{A_C}\right) = m_C \cdot c_p \cdot \frac{dT_{st}}{dt} + U_L \cdot (T_{st} - T_a).$$

The differential equations of heat balance (4) and (5) are solved by the finite difference method for a given time interval Δt [22], [23].

5. Presentation and discussion of the research results

Let us consider the operation of the heat supply system with a hybrid solar collector. In the morning, when there is not enough solar energy, there is no circulation in the circuit of the solar installation. The average temperature T_p of the absorber of the solar collector equals the average temperature T_{st} of the stationary heat carrier in it. With the increase in the amount of solar energy that falls on the collector, the temperature of the heat carrier in it increases and when it exceeds the average temperature T_S of the heat carrier at the outlet of HST by the value ΔT_{on}, i.e. under the condition $T_p - T_S \geq \Delta T_{on}$, automation equipment turns on the circulation pump. The turn-on time of the pump is determined by the differential equation of the heat balance (5) and the operation of the system is described by the differential equation of the heat balance (4). To avoid frequent pump turning on/off the temperature difference is set $\Delta T_{on} = 8 \ldots 11$ °C.

In the evening hours, as soon as the solar energy is not enough to maintain the efficient operation of the solar system, the automation equipment turns off the circulation pump. The differential thermostat compares the temperature of the heat carrier at the outlet from the solar collector T_{out} with the temperature of the heat carrier at the outlet from the HST T_S. The pump is turned off under the condition when $T_{out} - T_S \leq \Delta T_{off}$. It is recommended $\Delta T_{off} = 2$ °C.

The authors analyzed the change in the intensity of solar radiation I and the temperature of the ambient air T_a every hour and with a step of $\Delta t = 10$ s during July. Data on the hourly change of these parameters was taken from [23]. The values of the parameters with a step of $\Delta t = 10$ s were obtained by approximation of hourly data and presented in Fig. 2. As we can see from Fig. 2, the maximum intensity of radiation is observed between 11:00 a.m. and 2:00 p.m., and the highest daytime temperatures – between 2:00 p. m. and 5:00 p. m.

The performance of a hybrid solar collector depends on the area of the photovoltaic cells on it. The dimensionless parameter f shows the level of filling of the front side of the solar collector with photocells and is defined as

$$f = \frac{A_{pc}}{A_C}.$$

The thermal solar collector is without photocells at $f = 0$, and the whole area of the front side of the solar collector is filled with photocells at $f = 1$.

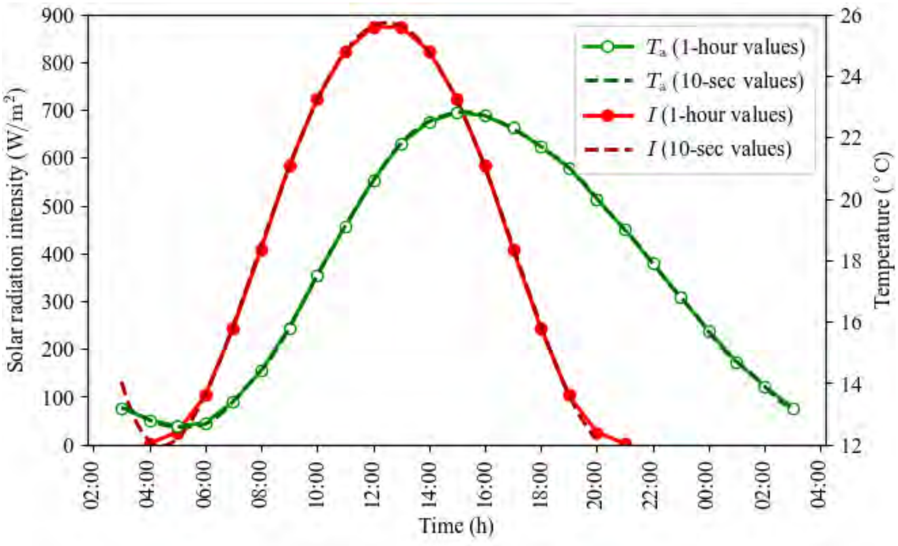

Fig. 2. The intensity of solar radiation I and the temperature of the outside air T_a, in July (hourly values and approximated values every 10 seconds).

The investigation is carried out for three values of water mass in HST M_S = 100 kg, 150 kg and 200 kg, five values of mass flow in the collector G = 0.01 kg/s, 0.03 kg/s, 0.05 kg/s, 0.07 kg/s and 0.09 kg/s and three values of the dimensionless parameter f = 0, 0.5 and 1. For a given area of the hybrid solar collector the mass of the heat carrier in it can be increased by increasing the number of pipes in its design, that is, by changing the step of their laying in the collector.

The authors analyzed the time of turning off the circulation pump t_{off} depending on the mass flow rate of the heat carrier in the hybrid solar collector G and the mass of water in the heat storage tank M_S which is shown in Fig. 3–5.

Figs. 3–5 show that the time of turning on the circulation pump t_{on} does not significantly depend on the mass of the heat carrier in the HST. At the same time, with an increase in the mass flow rate G, the time of turning off the pump t_{off} increases, and the time of turning on the pump t_{on} does not depend on it.

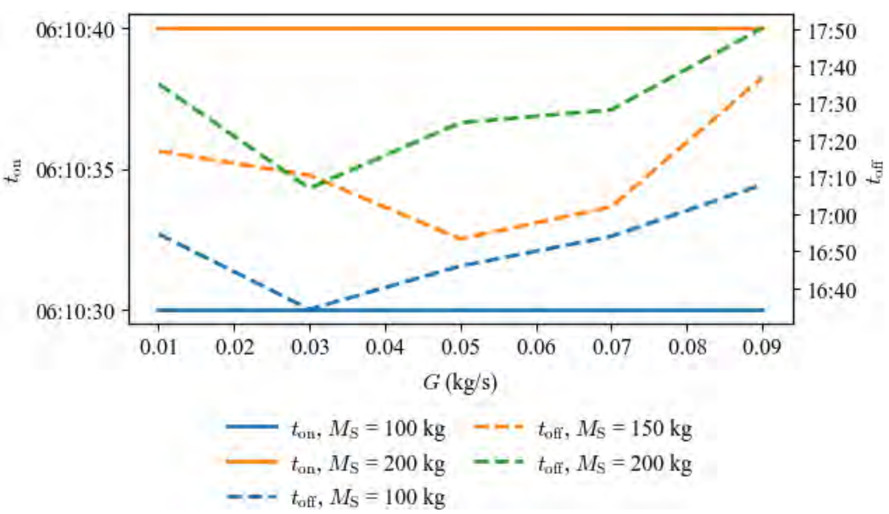

Fig. 3. The influence of the mass flow rate of the heat carrier in the hybrid solar collector G and the mass of the heat carrier in the storage tank M_S on the pump turning-on time t_{on} the pump turning-off time t_{off} for the level of photocells filling $f = 0$ in July.

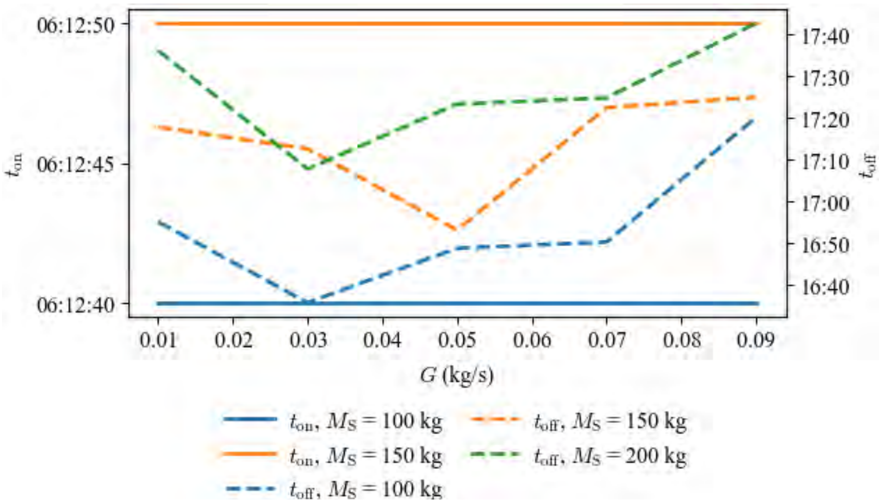

Fig. 4. The influence of the mass flow rate of the heat carrier in the hybrid solar collector G and the mass of the heat carrier in the storage tank M_S on the pump turning-on time t_{on} the pump turning-off time t_{off} for the level of photocells filling $f = 0.5$ in July.

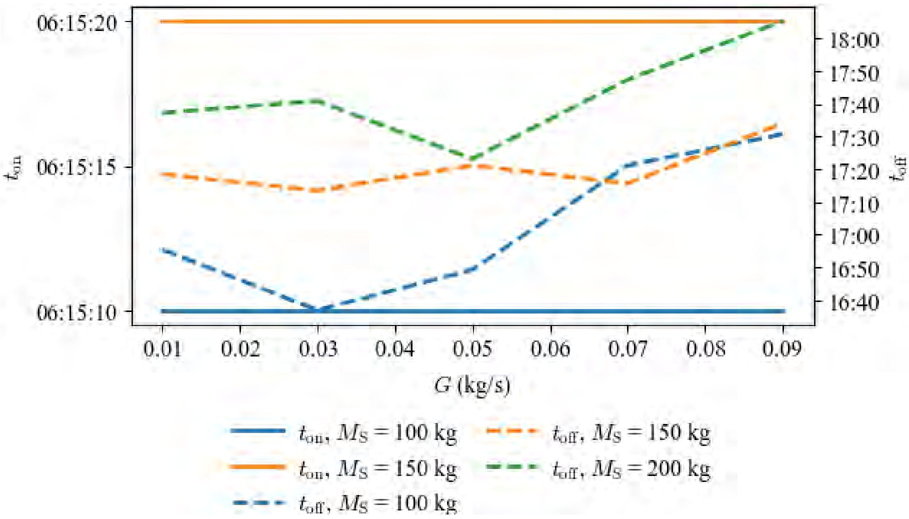

Fig. 5. The influence of the mass flow rate of the heat carrier in the hybrid solar collector G and the mass of the heat carrier in the storage tank M_S on the pump turning-on time t_{on} the pump turning-off time t_{off} for the level of photocells filling $f = 1$ in July.

Below, the authors estimate the change in the efficiency of the photocell η_{pc} and the change in thermal efficiency of the solar collector η_C when the parameters of the heat carrier change according to dependencies (3), (4). The iterative method is used to determine the efficiency of the photocell η_{pc} since it depends on the average temperature of the absorber T_p. The final value of photocell efficiency is determined by gradual approximations. First, it is assumed that $\eta_{pc} = 0.1$ then the differential equations (3), (4) are solved, and the average temperature T_p is calculated, then the new efficiency of the photocell η_{pc} is determined and then the calculations are repeated. The process of determining the new value η_{pc} is repeated until the difference between the previous and current value of the photocell efficiency becomes less than 1 %.

As G increases, the photocells efficiency η_{pc} is higher since the average temperature of the absorber T_p is lower. However, since the total operation time of the circulation pump is shorter, the total thermal efficiency of the solar collector η_C will be lower. Therefore, there must be an optimal heat carrier mass flow rate for which the collector thermal efficiency is maximum. This is evident from Fig. 6, which shows the dependence of the average daily thermal efficiency on the mass flow rate of the heat carrier in the collector.

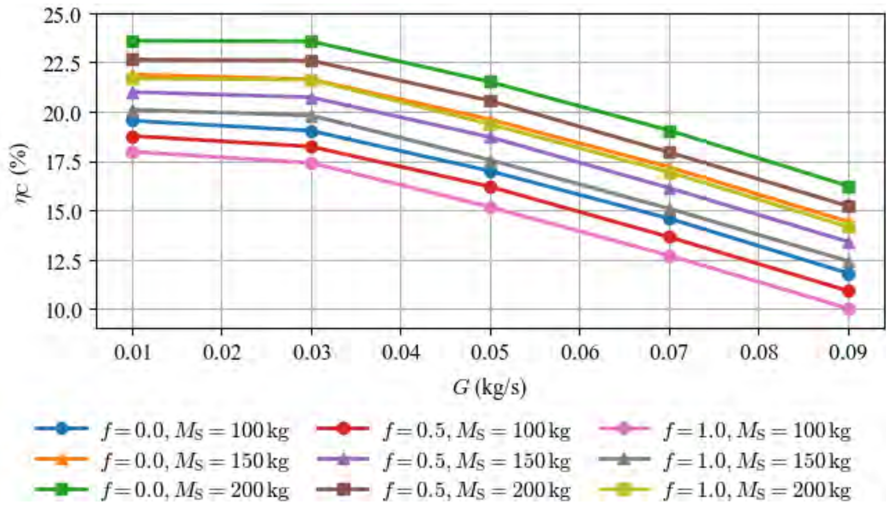

Fig. 6. The influence of the mass flow rate of the heat carrier G and the level of photocells filling f on the average daily thermal efficiency of the hybrid solar collector η_C for three values of heat carrier mass in HSTM_S in July.

Fig. 6 shows that the maximum thermal efficiency of the hybrid solar collector η_C is achieved when the mass flow G is less than 0.03 kg/s or 108 kg/h.

6. Conclusion

In the paper, the authors analyzed the theoretical basis for the hybrid solar collector in the heat supply system and investigated the effectiveness of its operation in various conditions using SolidWorks software and additional scripts programmed using Python.

During the computer simulation, the regimes with the different masses of water in the heat storage tank were analyzed, namely with 100, 150, 200 kg and with the different heat carrier mass flow rates in the collector: 0.01 kg/s, 0.03 kg/s, 0.05 kg/s, 0.07 kg/s and 0.09 kg/s at different values of the level f of photocells filling of the front side of the solar collector. The research results show that the turning-on time of the circulation pump does not significantly depend on the mass of the heat carrier in the heat storage tank. With an increase in the mass flow G, the turning-off time of the pump t_{off} increases, and the turning-on time of the pump t_{on} does not depend on it. It should also be noted that the increase in mass flow rate G results in a decrease in the efficiency of the solar collector η_C.

According to the results of the simulation and analysis of the obtained dependencies, the optimal operation mode of the hybrid solar collector was determined. The hybrid solar collector reaches the maximum thermal efficiency η_C at a mass flow rate of less than 0.03 kg/s.

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Моделювання роботи гібридного сонячного колектора в системі теплопостачання

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Анотація

Здійснено дослідження та моделювання ефективності гібридного сонячного колектора в системі теплопостачання, що складається із двох окремих блоків, а саме теплового акумулятора та плоского сонячного колектора, з'єднаних між собою трубопроводами. Виконано аналіз та розрахунок теплових параметрів системи упродовж однієї доби, визначено оптимальні значення витрати теплоносія у сонячному колекторі та маси теплоносія в тепловому акумуляторі з метою досягнення максимальної теплової ефективності. Автори використовують програмне забезпечення SolidWorks та додаткові скрипти, запрограмовані за допомогою Python для моделювання роботи сонячного колектора та обчислення його теплової ефективності. Результати дослідження свідчать про високий потенціал гібридних сонячних колекторів для ефективного генерування і акумулювання теплової енергії як для домогосподарств, так і для малої промисловості. Результати дослідження можуть бути корисними для інженерів і вчених, які працюють у сфері альтернативних джерел енергії та енергоефективних систем.

Ключові слова: гібридний сонячний колектор; система теплопостачання; тепловий бак-акумулятор; моделювання.