EEET ECOLOGICAL ENGINEERING & ENVIRONMENTAL TECHNOLOGY

Ecological Engineering & Environmental Technology 2021, 22(6), 122–130
https://doi.org/10.12912/27197050/142433
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Received: 2021.08.06
Accepted: 2021.09.14
Published: 2021.09.20

Pilot Tests of a Hybrid Solar Installation

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ABSTRACT

The article is devoted to the study of the efficiency of the structural elements of the solar collector in cloudy conditions with the stabilization of heat transfer due to the use of terrestrial radiation. The study involves experimental verification of theoretically obtained assumptions about the use of terrestrial radiation to improve the efficiency of the solar installation. Proposed a hybrid version of a solar installation using solar and terrestrial radiation. Based on the results of laboratory and field experimental tests, the efficiency of the offered hybrid installation is confirmed, positive results from short-term compensations of decrease in solar irradiation, e.g., due to clouds, are received. In addition to the known characteristics of heat collectors, for a hybrid installation, such a design parameter as the ratio of the heat capacity of the accumulator and the collector seems to be essential. The increase in the indicator characterizes the increase in the time of effective operation in the presence of clouds. The tests showed a significant impact on the operation of the installation of external factors such as the position of the Sun, ambient temperature, wind speed, etc. This will be taken into account in the further justification of the design of the hybrid installation and its parameters.

Keywords: solar installation, accumulator, heat collectors, experimental tests

INTRODUCTION

The issue of providing humanity with energy resources becomes more acute globally every year. There are two main aspects, namely the ever-increasing energy needs per capita, and aggravation of the global environmental situation related to the use of fossil non-renewable conventional resources. The outlook of transition to high-quality fusion energy remains remote due to significant research and technical problems of its implementation. The use of so-called inexhaustible energy resources: solar, wind, geothermal, etc. can be viewed as a partial solution to the environmental aspect of the problem. Thus, the creation of hybrid installations and design improvements of existing ones that use inexhaustible energy resources to ensure their reliable and uninterrupted operation is an urgent technical and economic issue that needs to be scientifically justified.

The International Energy Agency reported that in 2017, the buildings accounted for a third of the world's final energy demand. On-site renewable energy production can reduce electricity consumption in the buildings. According to the above study, a solar photovoltaic water heating system (S1), a solar thermal water heating system with electric booster (S2), a solar photovoltaic water heating system with electric booster (S3), and a built-in solar photovoltaic system and heat pump water heating system (S4) were analysed. The results show that S3 and S4 have "net" positive electricity generation, but their initial costs is higher, compared to other systems. For the buildings located in colder climates, S2 has lower values compared to S3, while the same system

(S3) has the lowest values for warmer climates (Haghighi et al., 2020).

A study on the choice of the justified length of the heat pipe condenser section. It has been experimentally established that the photothermal efficiency of the collector first increases and then decreases with increasing length; based on specific conditions, it is proposed to set the optimal length (Debnath et al., 2018). It was also found that when using the heat exchanger circuit with parallel connection of 5 or 7 pipes, the thermal effect changes slightly (Moslemi et al., 2018). Achieving the highest thermal efficiency of the collector is carried out by increasing the thermal conductivity of the filler materials in the gap between the copper plate and the absorbing surface. Compared with the use of advanced fluids and water as media, as well as the use of air, water, benzene and liquids from Na-k alloy separately in the air gap between the copper blade and the adsorbent surface, the efficiency of the collector will be increased by 10.4, 12.5, 10.8 and 10.8, respectively (Georgiev et al., 2020). The use of metal foams as radiators has great potential for further use in the areas such as solar thermal collectors (Bellos et al., 2017). The use of advanced fluids containing TiO_2 parts as a filler of the working body in a flat solar collector allows increasing the efficiency of the collector by approximately 45% and 17% with a volume fraction of 5% and 2.5% TiO_2 nanoparticles respectively (Panagiotidou et al., 2020). The search for the structural materials that are the most favourable for the operation of solar collectors, such as cellular polycarbonate plastics, for adsorption refrigeration systems, is underway. High optical efficiency and reduced heat loss coefficient of polymer solar collectors are obtained (Zhang et al., 2019).

The parameters of the location of the surfaces receiving solar radiation collectors, along with design features, are important indicators. The selected parameters include the angles of the collector (30°, 45° and 60°), single and double glazing, mass flow rate (0.0039–0.0118 kg/s), and two different plates of the absorber (flat and corrugated ones) (Moslemi et al., 2018). The daily performance of the collector is investigated throughout the year. The method of input/output performance in the concentrating collectors shall take into account the angle of incidence of the sun at sunny noon to achieve high efficiency (Mirmanto et al., 2016).

The accumulation of thermal energy allows compensating for the periodic atmospheric interferences of solar radiation. A design of heat accumulation installation consisting of a compression heat pump, a heat accumulator and an organic Rankine cycle is proposed. Analysis of the general thermodynamic potential and the limits of such a system using realistic simple Rankine cycles confirmed its feasibility (Ahmadlouydarab et al., 2020).

The choice of effective design schemes and parameters of solar installation functioning is rather reliably justified by modelling. Based on the numerical results, correlations of circulating flow rate and heat transfer were proposed. Circulating flow rate and heat transfer were correlated with solar energy input, reservoir temperature and pipe side ratio (Sukhyy et al., 2018a). A comparative experimental energy and exergy analysis of a photoelectric thermal air collector with a flat (model-I) and corrugated plates (model-II) as a solar thermal collector was performed. The analysis showed that at noon model II provides a higher yield of thermal energy, exergy and net electricity by 16%, 27.4% and 1.2% than in model I. The availability of a corrugated plate increases the magnitude of the pressure drop for model II than for model I. Despite meeting the requirement of higher pumping power, model II provides by 8.4% and 1.3% higher total thermal efficiency and total efficiency compared to model I (Bellos et al., 2017).

A modelled power plant that includes a 234 kW parabolic solar collector field, a 5 m^3 thermal energy storage, and a 5 kW ORC motor for thermal and electrical energy production. The modelling results represent small deviations from the actual data on the operation of the power plant in combination with the ORC motor, thus the model is considered reliable (Roskosch et al., 2020).

Using numerical methods and data from the literature, we calculated the efficiency, size reduction, cost and energy savings for different advanced fluids. According to the results of the study, it was calculated that 10,239 kg, 8,625 kg, 8,857 kg and 8,618 kg of total weight can be saved for CuO, SiO_2, TiO_2 and Al_2O_3, respectively. The average embodied energy of 220 MJ can be stored for each collector, a payback period of 2.4 years can be achieved, and an average of 170 kg less CO_2 emissions can be compensated for a solar collector based on advanced fluids compared to with a conventional solar collector (Prabhakar et al., 2019).

A review of modelling techniques and results also found no approaches to overcoming the negative impact of clouds on the efficiency of solar installations. To some extent, the answer to this question has been found in studies on hybrid solar installations where the use of solar energy is supplemented by other types of energy. A system with the following main components is proposed: a solar collector parabolic trough, an organic Rankine cycle controlled by stored solar energy and generating electricity, an electrolyser unit producing hydrogen from incoming water, a mechanical unit producing methane from released hydrogen and trapped carbon dioxide, a cooling/heating pump unit meeting the needs of a residential building. The results show that the proposed integrated energy system is a viable solution in the search for more efficient energy systems for the residential buildings (Faizal et al., 2013). This technical solution allows providing energy to consumers regardless of the level of solar radiation due to pre-stored methane. The disadvantage of the system is its complexity and high cost of creation and operation.

A developed and tested hybrid installation, including solar collectors and a heat pump with grounding is known. A design of a small hybrid installation containing day and seasonal storage and supporting five different modes of operation with an emphasis on charging the borehole heat exchanger, heating mode with ground heat pump and subsequent natural mode of operation/relaxation is presented. The study proves the need to charge the heat exchanger with solar thermal energy during the summer, mainly to avoid thermal depletion of the soil (Li et al., 2019). In fact, an installation of the described type operates as a heat pump, and solar energy is used to maintain stable operation of the geothermal heat exchanger in winter.

The authors propose to use the solar and terrestrial radiation in combination to obtain coolant with elevated temperature (Kostenko et al., 2020). Terrestrial radiation is derived from solar radiation, however is characterized by greater inertia, i.e. it is less dependent on the presence of clouds.

The installation (Kostenko et al., 2018) consists of a solar thermal collector, which contains a sealed housing with the upper part made of transparent material, and the inner surface facing the Sun has a dark coating. The housing has the inner pipes with ducts for the passage of the coolant, which have an inlet and outlet on the surface of the solar collector. The sealed housing of the collector is hinged to the bracket, which, in turn, is also hinged to the ground-mounted support riser, with adjacent heat accumulator. The heat accumulator is filled with a substance characterized by high thermal conductivity and heat capacity. The body of the solar collector is surrounded by a casing made of heat-insulating material, where the inner surface of the casing is covered with a light-reflecting layer, and the outer perimeter of the casing has dimensions and shape equal to the perimeter of the heat accumulator. This design has been improved (Kostenko et al., 2020) by providing for the storage of excess noon solar energy in the accumulator, which defines the increase in the efficiency of the installation after sunset or cloudiness. Structurally, the installation differs from the previous one in that the pipe for supplying heated coolant to the consumer is equipped with a valve; the heat accumulator has an additional heat exchanger inside, which inlet is connected to the outlet of the solar collector.

In normal operational mode, the valve located on the pipe for the output of the heated coolant is open, and the valve on the pipe connected to the outlet of the heat exchanger is closed. The transparent surface of the solar collector is irradiated with sunlight (Fig. 1).

The dark surface inside the collector's sealed housing absorbs rays with accumulation of heat in air, which heats the coolant inside the pipes, and the latter is supplied to the heat consumers. The heat accumulator is also exposed to the sunrays, and the substance filling it accumulates heat and reaches the temperature higher than that of the environment.

During the period of the highest daily solar activity, when the performance of the solar collector is maximum, it becomes possible to "recharge" the heat accumulator (Fig. 2). To do this, open the valve on the pipe connected to the outlet of the heat exchanger. In this case, the main flow of the coolant is supplied directly to the consumer, and its smaller portion is also supplied to the consumer in parallel flow through the heat exchanger located in the heat accumulator. This parallel flow gives off thermal energy to the substance inside the heat accumulator, heating it to a temperature close to that of the coolant.

When the Sun is covered with clouds, thus resulting in the decrease of intensity of irradiation of the transparent surface of the solar

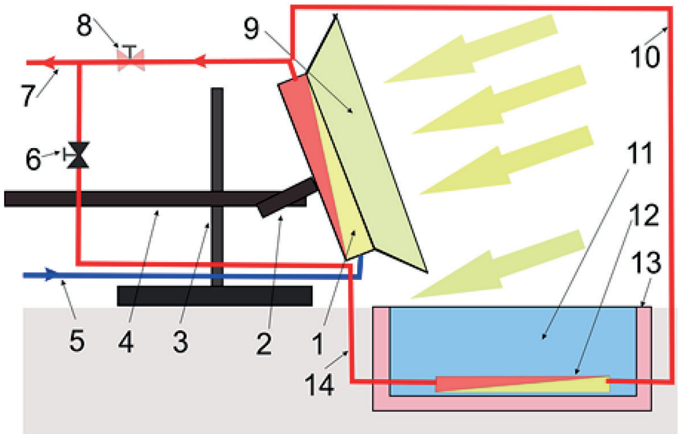

Figure 1. View of solar installation in normal sunlight (Kostenko et al., 2020): 1 – sealed housing, 2 – bracket, 3 – riser, 4 – rail, 5 – pipe, 6 – valve, 7 – pipe, 8 – valve, 9 – casing, 10 – pipe, 11 – heat accumulator, 12 – heat exchanger, 13 – thermal insulation layer, 14 – pipe

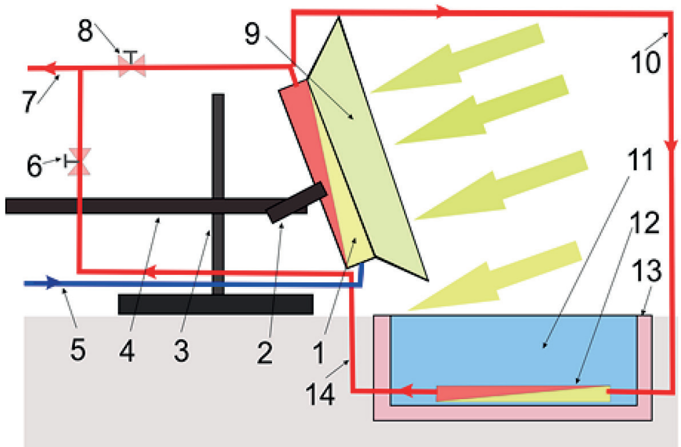

Figure 2. View of solar installation in the "recharge" mode of the accumulator (Kostenko et al., 2020): 1 – sealed housing, 2 – bracket, 3 – riser, 4 – rail, 5 – pipe, 6 – valve, 7 – pipe, 8 – valve, 9 – casing, 10 – pipe, 11 – heat accumulator, 12 – heat exchanger, 13 – thermal insulation layer, 14 – pipe

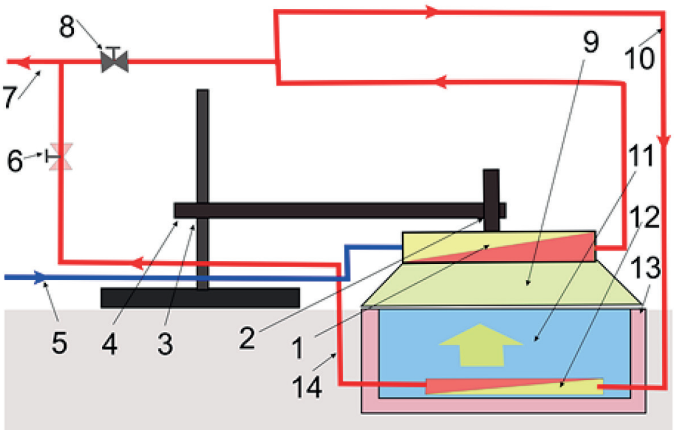

Figure 3. View of solar installation in the presence of clouds (Kostenko et al., 2020): 1 – sealed housing, 2 – bracket, 3 – riser, 4 – rail, 5 – pipe, 6 – valve, 7 – pipe, 8 – valve, 9 – casing, 10 – pipe, 11 – heat accumulator, 12 – heat exchanger, 13 – thermal insulation layer, 14 – pipe

collector, its thermal performance is reduced. In this case, the valve on the pipe directly connecting the solar collector to the consumer is closed, and the valve located on the pipe connecting the heat exchanger in the accumulator to the consumer is opened.

Then, by means of hinges on a riser and a bracket, the sealed housing of the solar collector is set over the accumulator so that the perimeters of a casing and the accumulator are aligned (Fig. 3). The size of the accumulator can be much larger than the transparent wall of the solar collector, which allows for increasing the heat capacity of the accumulator significantly.

The accumulated thermal energy, including additional energy, is supplied to the solar collector in the form of rays and convection fluxes.

The purpose of the research is to test the efficiency of operation of structural elements of the solar collector in the conditions of cloudiness with stabilization of heat transfer due to the use of terrestrial radiation. The influence of design factors on reducing the influence of clouds on the stability of the solar installation was taken into account.

METHODS

The research was conducted in the laboratory, where a small-scale physical analogue of the installation shown in Figures 1–3 was created. Glass laboratory refrigerators were used as a collector and a heat exchanger in the model, solar radiation was simulated using infrared heater "UFO" brand, an accumulator tank was simulated using a 20 l metal capacity of 20, and film and fabric was used as cover. Due to significant fluctuations in indoor air temperature and incoming water, the modelling results are given in relative terms (%). Field experimental research was carried out in Pokrovsk, Donetsk region, Ukraine, geographical coordinates: 48° E, 37° N.

A model of a solar installation consisting of a wooden body and an accumulator was created for field research. The body has the following dimensions: length – 80 cm, width – 60 cm, height – 20 cm. The bottom and sidewalls are covered with a layer of expanded polystyrene 6 mm thick; the surface of the layer is covered with a black plastic film. Inside the body there are 24 plastic pipes connected in series with an inner diameter of 16 mm and a length of 410 mm. The surface of the body is covered with glass 3 mm thick. The surface of the glass is oriented to the south. The angle of inclination to the horizon was 37°.

The accumulator has the form of a 50 l metal container with water. Expanded polystyrene 25 mm thick, located under the bottom of the container, and closed plastic vessels filled with water on the sides of the container were used as thermal insulation. Eighteen vessels with a capacity of 3 l are installed. During operation of the installation, the use of water vessels is provided in the warm season, when the air temperature is higher than the temperature entering the installation, the water is heated on an open surface and serves as an additional heat source. At low temperatures, empty containers provide additional thermal insulation.

To measure the water temperature in the solar collector, two electronic temperature sensors were installed; one measured the water temperature at the inlet to the installation, and the other - at its outlet. The indication from the sensors is displayed on digital boards. The outside air temperature was measured using a spirit thermometer. The consumption of coolant (water) was performed using a 10 l measuring tank and a stopwatch.

Measurements of solar radiation were performed using a BENETECH GM 1020 light meter which has a range of light level measurement from 0 to 200,000 Lux. Structurally, the light meter is made with a rotating light sensor for more convenient use of the device. A highly stable, durable silicon photodiode with a special corrective filter is used as a light sensor.

RESULTS AND DISCUSSION

The laboratory test results consist of three design options of a solar collector. Namely, the operation of the actual solar collector in the heating mode to the maximum temperature (see Fig. 1), followed by blocking the access of sunlight. The second option is the operation with a heat accumulator, when the collector was installed above the accumulator and covered with a heat-insulating fabric with a light-reflecting coating (see Fig. 2), the third - the same as a second, but with the connection of a built-in heat exchanger in the accumulator with thermal insulation (see Fig. 3).

The essence of the measurements was to heat the water in the collector to the maximum level using an IR source, after which the energy supply was cut off, and the dynamics of water temperature at the outlet of the installation was measured. In this way, the inertial performance of the installation was evaluated. The test results of these designs are given in Table 1.

It has been experimentally confirmed that the availability of an accumulator allows ensuring the effective operation of the model solar installation by 32 times relative to the version without an accumulator. Such an increase, of course, can be attributed to the large heat storage in a 20 l container with water, relative to the 0.2 l collector. That is, the indicators depend not only on the design of the installation, but also on the parameters of its elements.

An even greater effect was achieved after installing an additional heat exchanger in the accumulator with the supply of portion of the warm water from the collector. This allowed accelerating the heating inside the accumulator tank. Furthermore, the container was covered with a layer of insulating fabric, thereby reducing heat loss to the environment. As a result, the duration of complete cooling of the water before equalization at the inlet and outlet increased to 600 minutes, i.e. by 75 times, relative to the version without an accumulator.

Indicators of the effect of equalizing the decrease in output temperature due to fluctuations in the illumination of the collector significantly depend on the energy output of the accumulator. The heat capacity of the accumulator depends primarily on the amount of water it contains, i.e. the geometric dimensions relative to the collector surface. The second parameter is the water temperature in the accumulator. The amount of accumulated energy Q can be calculated according to the relationship known from physics:

$$Q = m \cdot c \cdot T,$$

where: m is the mass of water in the accumulator; c is its heat capacity; T is the difference between the initial and final water temperatures.

In the physical model, the ratio of the mass of water in the accumulator to that in the collector pipe was $n = 20/0.2 = 100$. This indicator provided a significant effect of inertial heating (after cutting the external source off) by more than 30 times. Additional heating of the contents of the accumulator by means of the heat exchanger located inside allowed heating water more evenly, and increasing heat accumulation. This resulted in an increase in inertial heating by 75 times.

In the field experiment carried out in July 2020 in anticyclone conditions, the performance of the test installation of the solar collector in cloudless weather during daylight hours was tested. The temperature of the water entering the solar installation was 24 °C, its flow rate was 0.2 l/min. Air temperature was 32 °C from 9:30 to 17:30. The total heating period lasted from 7:00 to 21:00. The maximum temperature level exceeding 50 °C was registered in the period from 13:00 to 15:00 (Fig. 4). If the consumer needs water with a temperature of about 40 °C, then for several hours, from 11:00 to 17:00, the excess heat can be used to “recharge” the accumulator.

In the presence of clouds, the operation of the solar installation was evaluated depending on the level of illumination of the transparent surface of the collector. The value of the temperature of

Table 1. Dynamics of water temperature at the outlet of models of various design options for solar installations after the IR irradiation is stopped

Without accumulator		With accumulator		With accumulator and heat exchanger	
Time, t, min	Temperature, T2, %	Time, t1, min	Temperature, T2, %	Time, t2, min	Temperature, T2, %
0	100	0	100	0	100
5	9	30	103	35	107
8	0	40	100	50	105
-	-	90	96	90	103
-	-	140	89	140	92
-	-	240	78	240	89
-	-	260	0	340	81
-	-	-	-	540	78
-	-	-	-	600	0

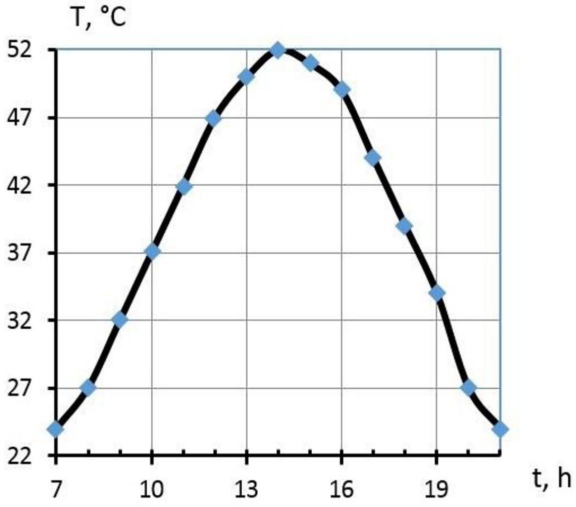

Figure 4. Dynamics of temperature (T, °C) at the outlet of the experimental solar collector during daylight hours (t, h), 25.07.2020

the water at the outlet from the container was impacted by fluctuations in ambient air temperatures and wind speed, the position of the Sun relative to the plane of the transparent surface of the container, as well as the temperature of the water at the inlet to the container. However, it is established that with increasing light level the water temperature increases exponentially (Fig. 5). The coefficient of reliability of the approximation is quite high R2= 0.8895.

The next step was to study the how the performance of the solar installation depends on the presence of clouds. Three possible situations were tested. At the initial stage, all three were performed in the same conditions. In sunny cloudless weather, water was supplied to the collector for about eleven hours, and for the next one and a half hours, the outlet water was heated to the maximum temperature. Then, without stopping the movement of water, the collector was covered with an opaque screen.

In the first case, the temperature of the water at the outlet of the collector without a heat accumulator was measured. After irradiation was stopped, cooling of water began almost immediately, in 30 minutes the temperature dropped by 5 °C; the equality of values at the input and at the output to 24 °C was recorded in 60 minutes (Fig. 6, solid curve). It was found that the inertial heating of water was due to the heat accumulated by the structural elements of the collector, namely the housing, glass, pipes, air trapped inside the housing.

In the next case, a heat accumulator was involved as a 50 l container with water. After the sun exposure was eliminated, the collector was mounted with its glass side towards the accumulator. The water cooled less rapidly than in the first case, in 30 minutes the temperature in the solar collector decreased by 2 °C. Complete cooling was recorded in 150 minutes, i.e. the accumulator heated the water for another 2 hours and 30 minutes (see Fig. 6, dotted line). The ratio of the mass of water in the accumulator to that which was in the collector pipe was n = 50/20 = 2.5. The relatively slow decrease in the outlet temperature to a level of about 32–35 °C can be explained by the heat exchange of the elements of the solar installation with the surrounding air, which had a high temperature of over 30 °C. After reaching a temperature close to the ambient air, the cooling rate increased. It is possible to predict less optimistic indicators of influence at low temperatures of ambient air.

The third option was implemented with the involvement of an additional thermally insulated

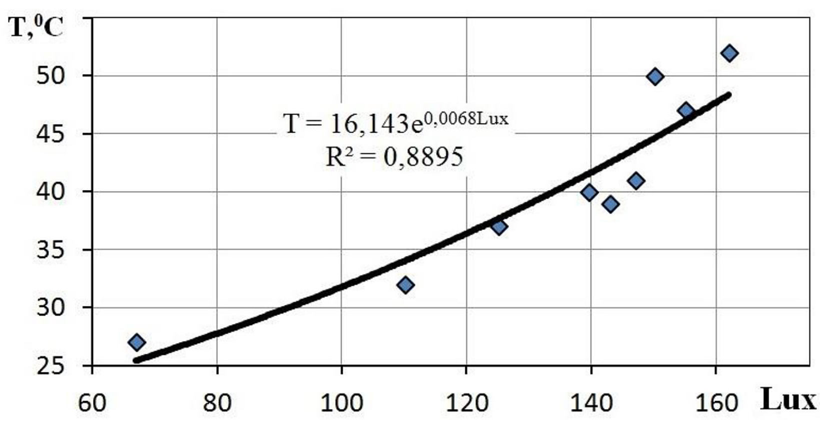

Figure 5. Dependence of the heating of the coolant (T, °C) on the illumination of the collector surface (Lux*1,000)

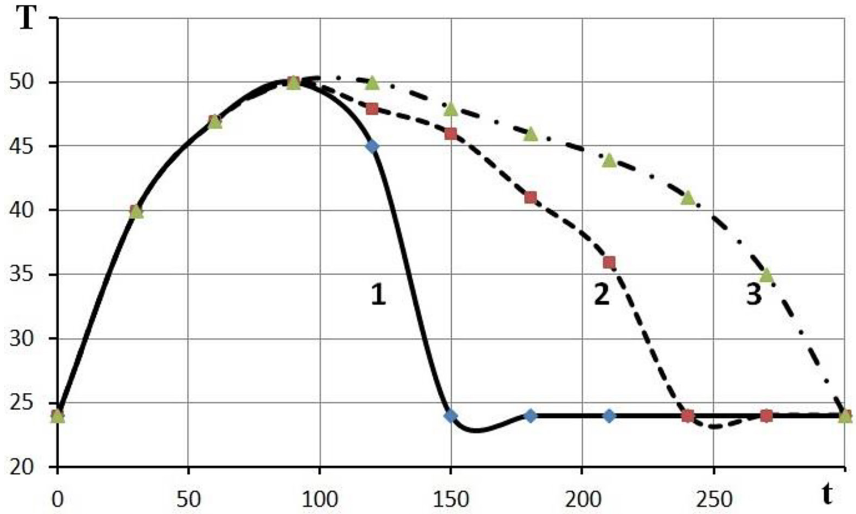

Figure 6. Dynamics of temperature (T, °C) at the outlet of the experimental solar collector during the simulation of clouds (t, min.) 1 – without accumulator; 2, 3 – with accumulator, without thermal insulation and heat-insulated, respectively

accumulator. A layer of foam under the bottom of the accumulator and containers with water surrounding its walls were used as thermal insulation. Such a solution helped to maintain the heated temperature in the solar collector for 30 minutes, after the sun was covered with the clouds. Cooling of water by 5 °C in this case occurred after 100 minutes, and complete cooling of water was recorded after 4 hours (see Figure 6, dashed line). Obviously, the thermal insulation layer slowed down the heat loss to the bottom, which improved the performance of the solar installation. Furthermore, the presence of additional vessels with a total capacity of 54 l, despite the imperfect contact between the accumulator capacity and the vessels, added energy. The illumination of the vessels was uneven around the perimeter of the container, however, the water temperature inside was not less than that of the ambient air. The ratio of the mass of water in the accumulator to that which was in the collector pipe can be estimated as $n = (50 + 54)/20 = 5.2$. It was found that such a design addition of the solar installation has significantly improved its performance.

If we consider the operation of the installation as a means of supplying hot water, e.g., for a shower with a temperature of about 33–36 °C, the use of the accumulator allows you to keep the operating water temperature by 3.2 times, and by 4.4 times with insulation, longer than without. Thus, it was found that the proposed design of the solar installation using terrestrial radiation is able to continue to operate effectively during certain time even with detrimental impact of clouds. To create prototypes of solar installations of the claimed design, it is necessary to conduct a thermal balance, taking into account both the design parameters of the components of the installation, and their dependence on the external conditions.

CONCLUSIONS

The analysis of up-to-date designs of the installations that use solar radiation for thermal energy production allowed establishing that they have a significant disadvantage, namely, a decrease in heat production due to the presence of clouds. We used of hybrid systems of two energy sources that allow equalizing fluctuations of the lighting conditions – using solar and terrestrial radiation.

The results of laboratory and field experimental tests shows, that the offered hybrid installation is efficient, because of short-term compensations of decrease in solar irradiation, e.g., due to clouds. In addition to the known characteristics of heat collectors, for a hybrid installation, such a design parameter as the ratio of the heat capacity of the accumulator and the collector seems to be essential. The increase in the indicator characterizes the increase in the time of effective operation in the presence of clouds. The tests showed a significant impact on the operation of the installation of external factors such as the position of the Sun, ambient temperature, wind speed, etc. This will be taken into account in the further justification of the design of the hybrid installation and its parameters.

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