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SOLAR INSTALLATIONS AND THEIR APPLICATION

Thermal Engineering and Technical-Economical Indicators of Seasonal Flat-Plate Capacitive Solar Water-Heating Collectors

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Abstract—The article presents the results of field experiments to determine the thermal and technical and economic indicators of flat capacitive solar-water heating collectors made of translucent plastics with bottom absorption of solar radiation for seasonal use in the regions of the Republic of Uzbekistan. As follows from the results during the warm season, the seasonal thermal efficiency in the reservoirs under consideration, depending on the thickness of the water layer for the season, respectively, is 17% at 0.05 m and 24% at 0.07 m. At the same time, the specific savings for natural gas from the Shurtan deposit and Angren coal deposit are 488 Nm^3 and 910 kg per season, respectively. The reduction of CO_2 emissions during the season during the combustion of natural gas from the Shurtan deposit is 667 kg and Angren coal deposit (depending on the percentage of carbon in the composition of coal) from 3148 to 4814 kg of CO_2, respectively.

Keywords: solar water-heating collector, flat-plate capacitive construction, hot water storage tank, heat output, thermal efficiency, thermal conductivity coefficient, frontal translucent cover, side insulation

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INTRODUCTION

The volume of investments in the use of renewable energy resources, in particular, in solar energy, is growing rapidly in the world, and the latter occupies one of the leading places in terms of the scale of their use. The depletion of traditional fossil resources on a global scale requires the introduction of solar-powered devices into practice [1], which, in turn, will save up to 60% of the primary energy resources spent in such systems due to the use of highly efficient solar technologies in hot water systems alone, and this figure can be further increased.

According to [2, 3], the total installed thermal capacity of flat-plate solar-water heating collectors (SWHCs) used in hot water supply systems in 2021 amounted to 501 GW (i.e., 715 million m^2) and the annual growth rate of their use in the period of 2011–2021 was 12.85%. It should be noted that special attention is paid to the problems of using solar energy as heat sources in hot water supply systems for residential buildings, public utilities, and social facilities. In this direction, comprehensive measures are being taken to develop regulatory documents and to expand the scope of application of new, highly efficient designs of flat solar water heating collectors and dual-circuit solar and solar-fuel systems based on them.

This paper presents the results of studies on the thermal calculation of SWHCs with capacitive absorbers of solar radiation with bottom absorption of solar radiation, and heat-insulated flat bases based on local building materials, which is the simplest design solution for manufacturing and operation. Note that due to the cost indicators of power plants, their large-scale use in hot water supply systems has been delayed.

In this regard, it is necessary to assess the main output, quantitative, and qualitative parameters of seasonal SWHCs in comparison with existing analogs.

METHODS AND MATERIALS

The results of experimental studies performed in natural conditions to determine the temperature regime of flat capacitive solar collectors with a solar radiation absorber (PSI), located horizontally in the meridian direction along the cardinal points, i.e., the long axis of the flat base of the collectors is directed from east to west (Fig. 1.).

Experimental studies were carried out in the climatic conditions of Gulistan (on the solar site of Gulistan State University) during the summer period of 2017–2019.

The purpose of conducting field experimental studies was:

Fig. 1. Flat plate solar water heating collector (SWHC) with a surface area of 5 m^2 with translucent coating.

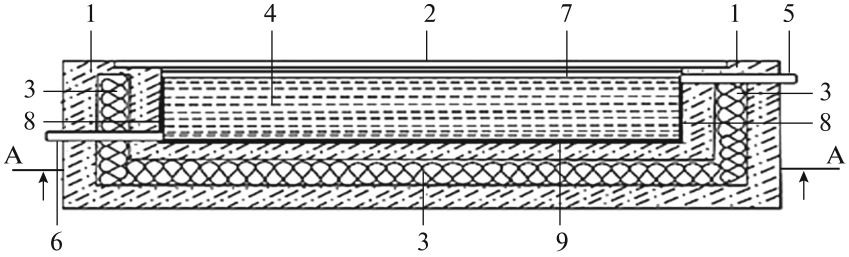

Fig. 2. Schematic diagram of a vertical section of an SWHC with capacitive PSI.

— Establishing the degree of dependence of the temperature of hot water in the SWHCs on the thickness of the water layer in the capacitive PSI.

— Determination of the thermal efficiency of the collectors of the type under consideration, depending on their overall dimensions and rational terms of their operation in seasonal hot water supply systems.

Figure 2 shows a schematic diagram of a pilot production sample of SWHCs with a capacitive PSI [4, 5], which consists of a body (*1*) made of concrete in the form of a box, on the bottom of which a container (*4*) is located, made of a polymer material with a translucent upper part (*7*), with an inlet (*5*) and outlet (*6*) nozzles; a layer of heat-insulating material (*3*) is placed inside the side walls and the bottom of the housing, while the collector housing is provided with a frontal translucent coating (TC) (*2*), and a black coating (*8*, *9*) is applied to the side and bottom parts of the container.

Reducing the heat losses of the housing in the SWHC under consideration is achieved, firstly, by placing a layer of heat-insulating material inside the side walls and at the bottom of the housing. The inner heat-insulating layer reduces the value of the generalized coefficient of thermal conductivity of the three-layer wall in comparison with the coefficient of thermal conductivity of the source material. The lower the thermal conductivity of the heat-insulating material, the lower the effective thermal conductivity and, accordingly, the lower the heat loss from the wall surface. From [6–8], it is known that the thermal conductivity of normal concrete is 1.5–2.1 W/(m K) and the thermal conductivity of reed plates –0.06 to 0.09 W/(m K) depending on the degree of compaction. The average difference in thermal conductivity values is ~23 W/(m K). Secondly, by the fact that the collector housing is equipped with a front joint venture and side thermal insulation, which additionally reduce the thermal losses of the housing.

To increase the efficiency of water heating in an SWHC, the side and lower parts of its PSI are made of black polymer material. In this case, the radiant flux of solar radiation passing through the upper translucent wall of the container and the water layer will be completely absorbed by the black side and bottom parts of the container. The main part of the absorbed solar radiation energy will be spent, first of all, on heating the water in the tank and only a small fraction of it will be transferred by thermal conductivity to the body. The effect of preferential heating of the water, rather than the body, is enhanced by natural thermogravitational convection as a result of which the side and lower parts of the tank are continuously washed by downward flows of cold water.

Determination of the Coefficient of Thermal Efficiency of SWHCs with capacitive PSI

Daily variations in water temperature (t_w) and accumulation of useful heat ($Q_{\text{use}_{9-15}}$) in flat SWHCs with capacitive absorbers of solar radiation with bottom radiation absorption are presented in [5].

The value of the coefficient of thermal efficiency of the SI receiver (η_tr) ceteris paribus (meaning δ_w, λ_w and $K^{\Sigma}_{\text{rc}_{\text{r-o}}}$, mainly depends on the heat transfer coefficient from the inner surface of the lower wall of the PSI to the water heated in it (α_{k_in}), and is defined as follows [6]:

$$\eta_\text{tr} = \left[1 + K^{\Sigma}_{\text{rc}_{\text{r-o}}}\left(\frac{\delta_\text{w}}{\lambda_\text{w}} + \frac{1}{\alpha_{k_\text{in}}}\right)\right]^{-1}, \tag{1}$$

where δ_w and λ_w are respectively, the thickness and thermal conductivity of the lower wall of the plastic PSI; α_{k_in}, is the heat transfer coefficient from the inner surface of the lower wall of the PSI to the water heated in it; and $K^{\Sigma}_{\text{rc}_{\text{r-o}}}$, is the coefficient of total heat losses.

To determine the value of α_{k_in} for a horizontal layer of still water in the range of the Prandtl number (Pr) from 0.6 to 2000 (heat is transferred to the heated water from below), we use the criterion equations proposed in [7, 8].

Due to the fact that the value Ra_ℓ for the case under consideration, is in the range of its change from 8×10^6 before 3×10^{10} values of α_{k_in} is determined by the following formula [9]:

$$\alpha_{k_\text{in}} = \overline{\text{Nu}}\frac{\lambda_\text{w}}{\ell} = 0.15\text{Ra}_\ell^{\frac{1}{3}}\frac{\lambda_\text{w}}{\ell}. \tag{2}$$

For values $\text{Ra}_\ell = 3.406 \times 10^8$, $\lambda_\text{w} = 64.475 \times 10^{-2}$ W/(m °C) (at $\overline{t}_\text{w} = 47°\text{C}$) And $\ell = 0.417$ m meaning α_{k_in}, determined by (2), is 162.0 W/m^2 °C.

For values $\delta_\text{w} = 0.0005$ m, $\lambda_\text{w} = 1.0$ W/m^2 °C, $K^{\Sigma}_{\text{rc}_{\text{r-o}}} = 6.766$ W/m^2 °C meaning η_tr, determined from (1), is 0.9568.

It is also of scientific interest to compare the values of α_{k_in} and η_tr for PSI of the SWHC type under consideration, when heat is supplied to the fixed water layer in the tank from above. The heat flow to the water is directed from top to bottom, and the value of α_{k_in} is determined from the criterion equations presented in [9].

According to the calculation results, at $\text{Ra}_\ell = 3.406 \times 10^8$ meaning α_{k_in}, determined by formula (2), is 64.75 W/m^2 °C , which is 2.5 times less compared to the case when the heat flow to the horizontal layer of still water is supplied from below, which is well confirmed by the data [10].

At $\alpha_{k_\text{in}} = 64.75$ W/m^2 °C and $K^{\Sigma}_{\text{rc}_{\text{r-o}}} = 6.766$ W/m^2 °C meaning η_tr, determined by (2), is 0.9026, which is 6% higher compared to the case when the heat flow to the horizontal water layer in the tank is supplied from above. These circumstances testify to the advantage of SWHCs with capacitive PSI with bottom absorption of solar radiation in comparison with streaming facial absorption of solar radiation.

EXPERIMENTAL

The results of the generalization of experimental data on determining the water temperature, the sum of the daily heat output and the average daily thermal efficiency of the SWHCs with capacitive PSI, during clear and semi-clear days of the period of 2017, taking into account the amount of incident solar radiation, the amount of useful energy, the thermal efficiency and the amount of hot water received per season, respectively, for $\delta_\text{w} = 0.05$ m and $\delta_\text{w} = 0.07$ m are presented in Table 1.

As can be seen from Table. 1, for the warm period of the year, the usefully obtained energy and thermal efficiency of the SWHC with capacitive PSI, depending on the thickness of the water layer for the season, are 76.99 MJ and 0.17 at $\delta_\text{w} = 0.05$ m and 94.81 MJ and 0.24 at $\delta_\text{w} = 0.07$ m, respectively.

In the process of experimental studies, every 30 min, the following were measured: the daily course of the flux density of the total solar radiation incident on the plane of the frontal (horizontal) surface of the collector (using a pyranometer $P = 80$ M), the temperature of the outside air and heated water in the collector using laboratory thermometers, and wind speed (using cup anemometer MS-13). Measurements began at 8 am and ended at 6 pm.

The amount of water poured into the experimental collectors and taken from them was measured by the weight method, and in the pilot production collector, only in the morning.

The root-mean-square error of measurements and calculations was determined on the basis of the relative errors of individual measurements and calculations, the main of which are:

Table 1. The daily amount of solar radiation incident on the surface of the collector and the amount of useful energy received, with $\delta_w = 0.05$ m and $\delta_w = 0.07$ m, respectively, per season

Experiment dates	Amount of days	$Q^{\Sigma}_{\mathrm{inc}_{9-15}}$, MJ	$Q_{\mathrm{use}_{9-15}}$, MJ		$\bar{\eta}_{9-15}$	
			0.05 m	0.07 m	0.05 m	0.07 m
05.2017	5	91.31	14.69	19.88	0.16	0.22
06.2017	5	101.51	17.19	23.39	0.17	0.23
07.2017	5	105.56	18.97	24.47	0.18	0.24
08.2017	5	84.53	16.75	26.27	0.20	0.31
09.2017	4	62.87	9.39	12.80	0.15	0.20
Per season	24	445.78	76.99	94.81	0.17	0.24

— Relative error when measuring the outdoor temperature using a meteorological mercury thermometer:

$$\delta_{t_o} = \frac{1 \times 100\%}{50} = 2.0\%.$$

— Relative error when measuring the temperature of cold and hot water using a laboratory mercury thermometer:

$$\delta_{t_w} = \frac{1 \times 100\%}{100} = 1.0\%.$$

— Relative error when measuring the volume of water in a capacitive receiver using measuring cylinders:

$$\delta_{\upsilon} = \frac{1 \times 100\%}{68} = 1.5\%.$$

— Relative error when measuring the arrival of the total SR using a pyranometer, according to passport data:

$$\delta_q = \pm 3.0\%.$$

The root-mean-square total error of measurements and calculations in this case is according to [11].

$$\bar{\delta}_{\mathrm{sq}} = \sqrt{\frac{\sum \delta_i^2}{n}}$$

$$= \sqrt{\frac{\delta_{t_o}^2 + \delta_{t_w}^2 + \delta_v^2 + \delta_q^2 + \delta_d^2 + \delta_\alpha^2 + \delta_g^2 + \delta_\upsilon^2}{8}} = 6.00\%.$$

Technical and Economic Indicators of the Installation

Based on the data in Table 1 we determine the expected technical and economic indicators of the reservoir in question. The amount of reference fuel saved from the use of the collector of the considered type, determined from [12–16] will be:

$$G^{\mathrm{spec}}_{\mathrm{r.f.}} = \frac{Q^{\mathrm{season}}_{\mathrm{use}}}{\eta_{\mathrm{rt}} q_{\mathrm{r.f.}}}, \quad (3)$$

with the efficiency of using low-power traditional heat sources (η_{tr}) 0.5, calorific value of reference fuel ($q_{\mathrm{r.f.}}$) 29.3076 GJ/t.o.e. at $\delta_w = 0.05$ m is 41.46 kg c.f./m^2 season and at $\delta_w = 0.07$ m is 48.6 kg c.f./m^2 season.

Experimental studies were conducted to determine the technical and economic indicators of SWHCs with a joint venture, which has a surface area of 5 m^2. We show that to create this type of collector, 0.44 m^3 of concrete is needed, which currently costs about \$30 in Uzbekistan. In turn, for one SWHC with a joint venture with an area of 5 m^2 we are spending \$20 including thermal insulation and without labor costs.

The average specific heat output of the considered collector with a total area of 5 m^2 is 71.4 MJ per day or 8353.8 MJ for the season. The amount of reference fuel saved from the use of the collector of the considered type is 570 kg c.e. for the season.

CONCLUSIONS

In the warm period of the year, the useful energy received and the thermal efficiency of the SWHC with capacitive PSI, depending on the thickness of the water layer for the season, are 76.99 MJ at $\delta_w = 0.05$ m and 94.81 MJ at $\delta_w = 0.07$ m, respectively.

In view of the foregoing, it should be noted that the specific savings of natural gas from the Shurtan field and Angren coal is 488 Nm^3 and 910 kg per season, respectively. Reduction of CO_2 emissions during the season when burning natural gas from the Shurtan field is 667 kg and Angren coal (depending on the percentage of carbon in the coal composition) from 3148 to 4814 kg CO_2, respectively. If the price is 1 Nm^3 gas for 50 cents, the price saved for 488 Nm^3 gas is \$23 USD.

Thus, depending on the change in prices for the cost of construction of the collector, the period for covering the costs is one season.

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