The efficiency of using a combined solar plant for the heat and humidity treatment of air

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Abstract. The authors of this work have proposed a combined solar heating unit for the heat and humidity treatment of greenhouse air supplies. The object of research is a combined solar collector for the simultaneous heating of water and air. The heat and humidity treatment of supply air is an energy-intensive technological process that requires a very large consumption of thermal energy and water resources. For the operation of such a system, electric heating installations are often used; however, these systems are not always available and economical. In this paper, to reduce the consumption of traditional energy for the heat treatment of the air supply, a combined solar collector is proposed, and the results of an experimental study of the operating modes of the installation in the conditions of the city of Karshi are presented. It has been developed combined solar collector, the temperature of the heat carriers at the outlet in the heating mode "water + air" reached up to 48 °С (air) and up to 60 °С (water), which are acceptable for air treatment systems of heat and humidity in greenhouses. As a result of the experimental studies, the high energy efficiency of the combined solar collector in the "water + air" heating mode is shown. It has been established that the efficiency of the installation is in the range of 0.45 - 0.69.

1. Introduction
In recent years, the world has seen a significant increase in the use of renewable energy sources, primarily solar energy. In the national energy programmers of the world’s long-term developed countries a significant expansion of the use of solar energy is provided. The main reason for this expansion is to increase energy security, reduce the energy intensity of the gross domestic product and prevent the environmental consequences caused by the large-scale use of natural hydrocarbon fuels [1].

Since 2000, the energy intensity of the gross domestic product of Uzbekistan has decreased from 0.98 to 0.48 f.o.e. thousand dollars, while the global average level is 0.21 f.o.e., meaning this value is 2-3 times higher than that in developed countries worldwide [2].

World experience shows that the use of renewable energy sources contributes to strengthening the energy security of a state, reducing the energy intensity of the gross domestic product, preserving the country's energy resources, reducing environmental stress, and reducing greenhouse gas emissions [3-4].
The Republic of Uzbekistan is located in relatively favourable climatic conditions (between 37° and 45° N and between 56° and 73° E) for the use of solar energy, the energy potential, of which is 98.5% of renewable energy sources [5-6].

Agricultural objects, including protected ground structures, are large consumers of traditional energy. Our studies show that the use of solar energy for the heat supply of autonomous agricultural facilities (greenhouse complexes, vegetable stores, drying of agricultural products, hot water supply systems for agricultural facilities, heat and humidity air treatment systems, etc.) will allow the replacement of up to 60-70% of the heat load of agricultural facility farms depending on the climatic location [7-11]. Therefore, the use of solar energy in the heat supply systems of agricultural buildings and structures far from a centralized energy supply is relevant.

One of the important tasks is to reduce the energy intensity of technological processes and increase the energy efficiency of greenhouses with the efficient use of solar energy. In this work, to ensure the saving of traditional energy in greenhouses, a system of heat and humidity air treatment with a combined water-air solar collector is proposed.

The purpose of this work is to perform an experimental study of the operating modes of a combined solar collector and assess its efficiency in the natural and climatic conditions of the city of Karshi.

2. Materials and methods
For the operation of a gel heating system for the heat and humidity treatment of air in greenhouses [11], we developed a combined solar collector (CSC) that simultaneously heats water and the atmospheric supply air (figure 1).

![Figure 1. Combined solar collector diagram: 1-tank of cold water; 2-combined solar collector; 3-water pump; 4-air fan.](image)

To calculate the thermal efficiency of a combined solar collector of a heat-and-humidity air processing system, the initial data included the following thermal engineering parameters: the ambient temperature, the value of total solar radiation falling on the radiation-receiving surface of the CSC the collector operation time, the coolant flow rate, the initial coolant temperature and the collector geometric dimensions. The thermal calculation of the heat balance of the combined solar collector was carried out according to a well-known method [12-18].
An experimental study of the thermal efficiency of the combined solar collector was carried out on an experimental installation in the natural and climatic conditions of the city of Karshi when the air treatment system of heat and humidity was operating.

When investigating the efficiency of air heating, air was supplied at ambient temperature. Temperature sensors and thermocouples in the KSP-4 set were installed on the pipeline no further than 10 cm from the entrance and exit of the solar collector. Water flow rates were measured with a Portaflow 330 ultrasonic flow metre (3% absolute error). In addition, the air consumption was measured using the AM-70 anemometer. The intensity of the intake of direct and scattered solar radiation was measured using a Mac Solar actinometer (Germany), and the results are presented in table 1.

| Table 1. Intensity of direct and scattered solar radiation on a horizontal surface in the city of Karshi, kJ/m² hour. |
|---|---|---|---|---|---|---|---|---|---|
| Month | January | February | March | April | May | June | July | August | September |
| Direct solar radiation | 1742 | 1850 | 1870 | 2056 | 3040 | 2980 | 2930 | 2700 | 2450 | 1850 | 1617 |
| Scattered solar radiation | 552 | 590 | 803 | 900 | 893 | 846 | 860 | 770 | 620 | 612 | 467 | 465 |
| Total solar radiation | 2294 | 2440 | 2673 | 2956 | 3473 | 3886 | 3840 | 3700 | 3320 | 3062 | 2317 | 2082 |

To assess the efficiency of the proposed thermal scheme for the simultaneous heating of two heat carriers (water + air) in the water-air collector, a comparison was made regarding the efficiency of the collectors when operating in water, air and water-air modes (Tables 2, 3 and 4, respectively). The experiments were carried out under the following conditions: air consumption - 0.05 m³/s; water consumption - 0.005 kg/s; the air temperature at the inlet was equal to the ambient temperature; and the water temperature was 20 °C.

3. Results and discussion

The thermal efficiency of the proposed combined solar collector depends on the solar energy potential of the area. Therefore, in table 1, the monthly average data for the intensity of direct, scattered and total solar radiation are presented.

The change in the mean monthly straight line scattered and total solar radiation on a horizontal surface in the city of Karshi shown in figure 2.

The heat absorbed by the solar collector, i.e., useful heat, was determined by the following formulas [19]:

- For water:
  \[ q_{water} = G_m \cdot c_p \cdot (t_2 - t_1) \cdot 10^3, W \] (1)

- For air:
  \[ q_{air} = G_{air} \cdot c_{p_{air}} \cdot \rho_{air} (t_2 - t_1) \cdot 10^3, W \] (2)
where $G_m$ is the mass flow rate of water, kg/sek; $c_{pw}$ is the specific heat of water, $c_{pw} = 4.19 \frac{kDJ}{kg \cdot °C}$; $t_1$ and $t_2$ are the temperatures of water and air at the collector inlet and outlet, respectively, °C; $G_{air}$ is the volumetric air flow through the SC, m$^3$/s; $c_{p_{air}}$ is the heat capacity of air, equal to $c_{p_{air}} = 1.07 \frac{kDJ}{kg \cdot °C}$; and $\rho_{air}$ is the air density, kg/m$^3$.

**Figure 2.** Change in the average monthly direct and scattered solar radiation on a horizontal surface in the city of Karshi.

The total radiation entering the collector is determined by the formula:

$$Q_r = q_r \cdot F_{col}, W$$  \hspace{1cm} (3)

where $q_r$ is the intensity of solar radiation per unit surface of the solar collector, W/m$^2$; and $F_{col}$ is the radiation receiving area of the collector, m$^2$.

Collector efficiency:

$$\eta = \frac{Q_{USEF}}{Q_r}.$$  \hspace{1cm} (4)

where $\eta$ is the collector efficiency; $Q_{USEF}$ is the useful heat absorbed by the collector, W; and $Q_r$ is the intensity of the total solar radiation flux on the collector area, W.

The results of the experiments and calculations using the above formulas are shown in tables 2, 3, 4 and figure 3, 4.

**Table 2.** Results of an experimental study of a combined solar collector in the air heating mode (August 2020).
The local time  | Inlet air temperature, $t_1$, °C | Air flow, $G_{air}$, m$^3$/s | Outlet air temperature, $t_2$, °C | Heat absorbed by the collector, $Q_{usef}$, W | Total solar radiation flux intensity per collector area, $Q_c$, W | Collector efficiency, $\eta$
--- | --- | --- | --- | --- | --- | ---
9:00 | 24 | 0.05 | 26 | 138 | 980 | 0.14
10:00 | 30 | 0.05 | 34 | 276 | 1200 | 0.23
11:00 | 34 | 0.05 | 39 | 345 | 1215 | 0.29
12:00 | 36 | 0.05 | 42.5 | 448 | 1400 | 0.32
13:00 | 40 | 0.05 | 47.5 | 517 | 1500 | 0.35
14:00 | 38 | 0.05 | 48 | 690 | 1550 | 0.44
15:00 | 37 | 0.05 | 46 | 621 | 1480 | 0.41
16:00 | 34 | 0.05 | 40 | 414 | 1420 | 0.29
17:00 | 31 | 0.05 | 36 | 345 | 1400 | 0.24
18:00 | 30 | 0.05 | 33 | 207 | 1200 | 0.17

Table 3. Results of an experimental study of a combined solar collector in the water heating mode (August 2020).

The local time  | Inlet water temperature, $t_1$, °C | Water consumption, $G_m$, kg/s | Outlet water temperature, $t_2$, °C | Heat absorbed by the collector, $Q_{usef}$, W | Total solar radiation flux intensity per collector area, $Q_c$, W | Collector efficiency $\eta$
--- | --- | --- | --- | --- | --- | ---
9:00 | 20 | 0,005 | 32 | 251 | 980 | 0.26
10:00 | 20 | 0,005 | 36 | 335 | 1200 | 0.28
11:00 | 20 | 0,005 | 41 | 439 | 1215 | 0.36
12:00 | 20 | 0,005 | 45 | 523 | 1400 | 0.37
13:00 | 21 | 0,005 | 50 | 607 | 1500 | 0.40
14:00 | 21 | 0,005 | 60 | 817 | 1550 | 0.53
15:00 | 21 | 0,005 | 48 | 565 | 1480 | 0.38
16:00 | 20 | 0,005 | 42 | 460 | 1420 | 0.32
17:00 | 20 | 0,005 | 38 | 377 | 1400 | 0.27
18:00 | 20 | 0,005 | 28 | 167 | 1200 | 0.14

Figure 3. Graph of changes in the temperature of water and air at the inlet of the SC.
Figure 4. Graph of temperature change for “water + air” at the outlet of CSC in heating mode.

Table 4. Results of an experimental study of a combined solar collector in the “water + air” heating mode (August 2020).

| The local time | Outlet water temperature, $t_1$, °C | Outlet air temperature, $t_2$, °C | Heat absorbed by water, $Q_{\text{water}}$, W | Heat absorbed by air, $Q_{\text{air}}$, W | Heat absorbed by the collector, $Q_{\text{c}}$, W | Total solar radiation flux intensity per collector area, $Q_\lambda$, W | Collector efficiency $\eta$ |
|----------------|-----------------------------------|-----------------------------------|---------------------------------------------|---------------------------------------------|---------------------------------------------|-----------------------------------------------|-----------------------------|
| 9:00           | 30                                | 25                                | 209                                         | 69                                         | 278                                         | 980                                           | 0.28                        |
| 10:00          | 34                                | 32                                | 293                                         | 138                                        | 431                                         | 1200                                          | 0.36                        |
| 11:00          | 39.5                              | 37                                | 303                                         | 207                                        | 510                                         | 1215                                          | 0.41                        |
| 12:00          | 43                                | 41                                | 272                                         | 345                                        | 617                                         | 1400                                          | 0.44                        |
| 13:00          | 48.5                              | 46                                | 576                                         | 414                                        | 990                                         | 1500                                          | 0.66                        |
| 14:00          | 58.5                              | 42                                | 785                                         | 276                                        | 1061                                        | 1550                                          | 0.69                        |
| 15:00          | 46                                | 42                                | 523                                         | 345                                        | 868                                         | 1480                                          | 0.58                        |
| 16:00          | 40.5                              | 38                                | 419                                         | 276                                        | 695                                         | 1420                                          | 0.49                        |
| 17:00          | 36                                | 34                                | 335                                         | 207                                        | 542                                         | 1400                                          | 0.38                        |
| 18:00          | 26                                | 32                                | 125                                         | 138                                        | 263                                         | 1200                                          | 0.21                        |

4. Conclusion

Based on the studies carried out, the range of changes in the mass flow rate of water was estimated. It was shown that in operating modes for a solar collector with an area of 2 m$^2$, the water consumption varied from 0.005 to 0.008 kg/s, depending on the required temperature of heating the coolant at the outlet of the solar collector.

It has been established that in the developed combined solar collector, the temperature of the heat carriers at the outlet in the heating mode "water + air" reached up to 48 °C (air) and up to 60 °C (water), which are acceptable for air treatment systems of heat and humidity in greenhouses.

Experimental studies have shown the efficiency of the combined solar collector in the "water + air" heating mode is higher than that of similar water and air collectors. The average daily efficiency of the combined solar collector in the air heating mode was $\bar{\eta} = 0.28$ and that in the water heating mode was $\bar{\eta} = 0.33$. The average daily efficiency of the developed combined solar collector in the "water + air" heating mode was $\bar{\eta}_{c}^{\text{CSC}} = 0.45$.

Experimental studies showed that the average daily efficiency of the combined solar collector was $\bar{\eta}_{\text{day}} = 0.45$, i.e., 35% greater than that of the same solar collector, and 26.6% greater than that of the same water solar collector.
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