Water-air regenerative heat exchanger with increased heat exchange efficiency

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Abstract. According to experts' forecasts, by 2040 the global demand for energy will increase by 37%, and renewable energy sources in the next 20 years will become the fastest growing segment of the world energy, their share in the next decade will grow by about one and a half times. Solar energy is the fastest growing industry among all non-conventional energy sources and is gaining the highest rates of development in comparison with other renewable energy sources. In this article, the authors provide an overview of the technologies that increase the efficiency and productivity of solar panels, only the investigated methods are described that can speed up the process of introducing solar energy instead of traditional. All the methods described can increase the efficiency of systems that are based on the use of the sun as the main source of energy. The authors presented and described the scheme of a solar-air thermal power plant, which will improve energy efficiency through the use of a regenerative air solar collector with increased heat transfer efficiency. Strengthening will be achieved through the use of hemispherical depressions on the surface that receives solar radiation. A schematic diagram is given and the principle of operation of such a solar collector is described in detail. A comparative calculation of the intensification of the solar collector with the use of depressions and without the use as modernization was carried out, on the basis of which a conclusion was made about the efficiency of using this type of solar collector and the economic effect from the application of this method. A description of the method for calculating the solar collector is given, thanks to which this development can be used and implemented in existing heating and hot water supply systems.

1 Introduction

Today, non-traditional and renewable energy sources are very popular all over the world. According to experts' forecasts, renewable energy sources in the next 20 years will become the fastest growing segment of the world energy, their share in the next decade will grow by about one and a half times [1]. Around the world, solar energy is gaining the highest rate of development in comparison with other types of renewable energy sources. This is due to a number of factors: environmental friendliness of the technology, high reliability of the solar battery, autonomy of power supply to the energy consumer, the presence of an endless source of energy, as well as the absence of noise during operation. Germany leads the world in the

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use of solar energy, followed by China, Italy, Japan, the USA, Spain, France and other countries. [2]

The policy of countries in which non-traditional energy is actively developing, in particular solar, is aimed at the development and widespread introduction of renewable energy sources into people's lives. For example, China, the United States and the European Union are already actively studying the power of devices and mechanisms from solar energy. This means that in developed countries not only the issue of introducing solar energy instead of traditional energy sources is being studied, but also the issues of modernizing and improving existing methods. Therefore, the scientists of these countries are faced with the question of studying and researching various ways by which it is possible not only to increase the efficiency of solar power plants, but also to increase their power and energy intensity.

There are many possible ways to improve the operation of solar collectors - the use of various kinds of concentrators, optimization of tracking the position of the sun, the choice of the tilt angle and orientation of the solar collector. In addition to optimizing the methods for positioning the solar collector, methods for improving their design are also widely studied. The possibility of using new materials in the production of various elements is being studied; designs of polymer solar collectors, which are twice cheaper than conventional ones, are proposed. A large number of modern developments are devoted to the issue of increasing the efficiency of autonomous heat supply installations based on solar power plants [3-5]. Foreign authors studying solar energy pay attention to the assessment of solar radiation [6-9]. There are several ways to assess data on solar radiation fluxes: analytical; direct measurements on site; long-term measurements using a unified technique at meteorological stations.

One of the most urgent is the issue of researching algorithms based on the analytical interpretation of the sun's motion [10, 11]. Some authors for this method use the function of the average monthly intensity of solar radiation, but this approach is ineffective and is subject to serious criticism from researchers since hourly fluctuations are not taken into account [10-22].

All the necessary parameters of a specific geographic point can be determined by calculation. The general laws considered in [23] determine the parameters of the Sun's motion over the horizon, the energy [24, 25] and spectral characteristics of radiation [26-28]. In [29], the thermodynamic parameters of effective absorption are considered. The Universities of Minnesota and Hanevelt have considered the coefficients of effective absorption of the normal spectrum of solar radiation for the main selective coatings [30-32].

The latter method - direct measurement on site - is the most laborious of all, but it has been used by a number of researchers, both foreign [33-36] and domestic [37]. At present, the World Radiation Data Center (WRDC) has an information retrieval system with an archive and a systematically updated database on the components of the radiation balance of the world actinometric network. [38, 39] The main elements of this network are actinometric installations [40-43], which determine the parameters of direct and scattered solar radiation. In addition, there are private databases of renewable energy resources [44-50]. Much attention is paid to solar installations of a separate type, where the accumulator is located separately from the collector [51, 52], the most common of them are vacuum tubular solar collectors, which occupy more than 60% of the market [53]. One of the main tasks of the development of solar energy is to increase the capacity of solar plants, which will lead to an increase in their economic performance [54-57]. Self-draining solar heat supply systems are also being actively studied, a feature of which is the emptying of solar collectors from the coolant when the solar circuit pump stops in a special tank / storage tank.

A significant number of foreign developments are devoted to the development of the "Solar House" system, the essence of which is that electricity, water supply and heating are provided by the energy of the sun. In the United States, a special competition has even been established that brings together 20 international university teams in the fight to create the

most attractive and energy efficient solar houses, which also significantly reduce greenhouse gas emissions into the atmosphere [58-62].

All of the above research and development is only a small part devoted to the study of the issue of the development of unconventional and renewable energy sources, namely solar energy. Such a great interest in this problem once again confirms the relevance of the study and use of RES in the modern world.

2 Research methodology

This article proposes a method of using a regenerative air solar collector with increased heat transfer efficiency. This heat exchanger (Fig. 1) is designed to improve the efficiency of the implementation of the scheme of an energy-efficient solar-air heating installation. A distinctive feature of this heat exchanger is the ability to simultaneously heat two types of heat transfer fluids. It is proposed to use hemispherical recesses as intensifiers. A detailed description of this type of intensifier is presented in [64].

Fig. 1. Water-air regenerative heat exchanger with increased heat exchange efficiency:
1 - insulation; 2, 3 - glass; 4 - vacuum; 5 - air passage; 6 - sun-perceiving surface; 7 - tube; 8 spherical intensifiers

The operation of the solar collector with the use of hemispherical depressions is as follows (Fig. 1): the radiation of the Sun, passing through the glass, heats the absorber, which in turn heats the gaseous medium (air) moving in the gas heating cavity 5, while the hemispherical depressions 8 on the sun-perceiving surface 6 will contribute to a significant intensification of heat transfer. The coolant in the collector circulates through a harp-shaped pipe system, and since they are recessed by 50% into the sun-sensing plate, they will heat up, and the hemispherical recesses applied to the inner surface of the tubes will also contribute to the intensification of heat transfer. An increase in the efficiency of heat transfer in the developed collector is determined by a local increase in the heat transfer coefficient and an increase in the area. The growth of the heat transfer coefficient can be determined on the basis of experimental data, or by calculation.

3 Research results

To understand how effective intensification is, it is necessary to calculate the daily heat absorption of a flat water-air collector with and without modernization [64]. The calculation was made using [65] under comparable conditions.

Climatological data: Chita: longitude - 113 hours 23 minutes, latitude - 52 hours 6 minutes;date October 1, 2013

Surface direction: tilt angle to the horizon - 45 degrees; azimuth direction 180 deg.

Plate: plate dimensions are taken: 1000 * 100 * 10mm, material - copper, wall thickness 2mm.

Tubes: quantity 10 pcs., diameter 25mm, material - copper, wall thickness 1mm; coverage share 50%; thermal interface material - tin, layer thickness 500 microns.

Absorber: coloring - matt black paint (absorption rate 95, blackness 5, selectivity 0.4);

External insulation: glass - two layers, thickness 1 mm, attenuation coefficient 0.4 l / mm; air passage size 30 mm.

Air parameters: inlet air temperature 0 0C; air consumption - 100.0 m3 / h.

The results of calculating the daily heat perception of a flat water-air collector are summarized in Table 1.

Table 1. Results of calculating a flat reservoir without stimulation. Inlet air temperature / ambient temperature 0° C

№	The local time	Warmth is beneficially perceived collector, W
1	9:00	0
2	10:00	150
3	11:00	362
4	12:00	550
5	13:00	625
6	14:00	670
7	15:00	655
8	16:00	585
9	17:00	455
10	18:00	260
11	19:00	50
12	20:00	0
13	Total per day	4362

When calculating the daily heat perception of a regenerative water-air heat exchanger with an increased heat transfer efficiency, the heat transfer coefficients obtained by the standard method increase in proportion to the average (over the hole surface) relative heat

transfer coefficients. To take into account the increase in the heat exchange area, it is necessary to estimate its relative increase in K_F and take it into account in the standard procedure.

For the proposed geometric parameters of hemispherical depressions, K_F takes values from 1.09 to 1.116, depending on the packing density (for a preliminary estimate, $K_F = 1.1$ was taken in the calculations). The calculations showed that the flow regime is turbulent: $Re = 69636.4$. For such a regime, with intensification on spherical intensifiers, we take [67] $\alpha = 1.25$. The results of calculating the daily heat perception of a flat water-air collector with an increased heat transfer efficiency are summarized in Table 2.

Table 2. Results of calculating a flat reservoir (intensification: $K_F = 1.1$, $\alpha = 1.25$). Inlet air temperature / ambient temperature 0 °C

№	The local time	Warmth is beneficially perceived collector, W
1	9:00	0
2	10:00	152
3	11:00	377
4	12:00	590
5	13:00	635
6	14:00	675
7	15:00	660
8	16:00	595
9	17:00	465
10	18:00	267
11	19:00	52
12	20:00	0
13	Total per day	4468

The intensification showed a 2.43% increase in efficiency. The annual efficiency of reservoir intensification will be 106 kW / m². At the current tariff for the district heating system in Chita, 1925 rubles / Gcal, the economic effect is 175.5 rubles / m².

4 Discussion of the results

To use the solar air heating installation scheme, it is necessary to calculate the collector. When calculating the solar collector of a solar air heating system, the initial data are: the parameters of the collector, the flow rate of the intermediate heat carrier and air, the characteristic of the time interval, as well as the outside air temperature. Based on the calculation of the storage tank, the temperature of the intermediate heat carrier at the outlet

from it is determined. The result of the calculation is the temperature of the intermediate heat carrier at the inlet to the tank, as well as the air temperature at the outlet.

The basis for calculating the solar collector at a particular moment in time is the characteristic of the intensity of the actual solar radiation incident on the ray-receiving surface, taking into account its installation.

Thermal balance of the combined collector:

$$Q_{u3l} = Q_{\text{go3d}} + Q_{nl} + Q^{nom}, \quad (1)$$

where $Q_{u3l} = I \cdot F$ - the amount of heat entering the effective area occupied by the receiver;

Q_{go3d} - the amount of heat received by the air flowing through the collector;

Q_{nl} - the amount of heat received by the plate;

Q^{nom} - heat loss to the environment.

In the general case, air receives heat due to the absorption of radiation energy and due to convective heat exchange with the ray-receiving plate:

$$Q_{\text{go3d}} = Q_{\text{go3d}}^{u3l} + Q_{\text{go3d}}^{koh6}, \quad (2)$$

The amount of heat by radiation that has passed through a double transparent coating, assuming the properties of the coating are the same, and is beneficially perceived by both heat transfer fluids

$$Q_{nol} = Q_{u3l} \cdot D^2 - Q^{nom} = Q_{\text{go3d}}^{u3l} + Q_{\text{go3d}}^{koh6} + Q_{nl}, \quad (3)$$

where D - transparent coating transmittance.

Since the thickness of the air layer between the plate and the transparent coating is small, we assume $Q_{\text{go3d}}^{u3l} = 0$. Since the air velocity does not exceed Mach 0.25, its flow is assumed to be indistinguishable from the flow of an incompressible fluid.

Heating temperature of the radiation receiving plate t_{nl} is a variable and depends on the characteristics of the collector and the current intensity of solar radiation. Mean t_{nl} can be found subject to change Q_{u3l} , reducing addition $t = f(Q_{u3l})$ к $t = f(\tau)$, get:

$$\bar{t}_{nl} = \left(t_{nl}^{\max} - t_{\text{go3d-nochb}} \right) \cdot \sin \left(\frac{\tau - S_{\text{go3d}}}{S_{\text{3axod}} - S_{\text{go3d}}} \right) + t_{\text{go3d-nochb}}, \quad (4)$$

where $t_{\text{go3d-nochb}}$ - air temperature at night.

The amount of heat absorbed by the air can be found using the method of successive approximations, the essence of which is that, having previously set the temperature of the air at the outlet, we find the total amount of heat:

$$Q_{\text{go3d}} = w_{\text{go3d}} \cdot \rho_{\text{go3d}} \cdot f_{\text{go3d}} \cdot c_{p\text{go3d}} \cdot \left(t_{\text{go3d}}^{\text{назр}} - t_{\text{окр}} \right) \cdot n, \quad (5)$$

where w_{go3d} - fan-determined air velocity in the duct with cross-section f_{go3d} ;

ρ_{go3d} - air density;

$c_{p\text{go3d}}$ - isobaric heat capacity of air;

$t_{\text{go3d}}^{\text{назр}}$ - temperature of the heated air at the outlet of the manifold;

n - the number of parallel-connected radiation-receiving plates.

Or the amount of heat transferred by a heated plate to the air flowing along it in a given section of the plate:

$$dQ_{6030}^{конв} = \alpha_{6030} \cdot k_F \cdot b_{nl} \cdot (t_{nl}(l) - t_{6030}(l))dl, \quad (6)$$

where α_{6030} – heat transfer coefficient from the plate to air;
 b_{nl} – plate width;
 t_{nl} – plate temperature, variable along the length due to cooling by washing air;
 t_{6030} – heated air temperature;
 l – length of the radiation receiving area of the plate;
 k_F – the coefficient of the convective heat exchange area, taking into account the washing with air from both sides and the increase in the area due to intensification (corrugated or well). Integrating this equation along the length, we obtain Q_{6030} or, taking as a first approximation $t_{6030}(l)$, equal to the mean rhythmic temperature, or breaking the plate into sections.

After finding $Q_{6030}^{конв}$ by ur. (6) we compare it with the one obtained earlier and, if there is a discrepancy, we specify the air temperature at the outlet. If the values coincide, then we calculate the heat loss by radiation from the plate on both sides, taking into account double glazing, as well as the heat loss with reflected radiation.

$$Q_{nl}^{nom.omp} = (1 - \varepsilon_i) \cdot Q_{u3l} \cdot n. \quad (7)$$

Then we determine the amount of heat, as a result, perceived by the plate:

$$Q_{nl} = Q_{u3l} \cdot D^2 - Q_{6030} - Q^{nom}, \quad (8)$$

The temperature of the intermediate heat carrier at the outlet of the collector is determined by ur. (9):

$$Z_{hor} = x \cdot \cos(\text{lat}) + z \cdot \sin(\text{lat}) \quad (9)$$

and the temperature at the inlet to the tank or to the first stage of the heater for air heating according to ur. (10):

$$h = \arcsin(Z_{hor}) \quad (10)$$

Knowing the methodology for calculating the solar collector, we can use the scheme of an energy efficient solar air heating installation and implement it in air heating systems, which will significantly increase the efficiency of such systems, and we can also reduce the use of traditional heat sources.

5 Conclusions

Solar energy is the most affordable and widespread form of all existing energy resources. Many countries are actively pursuing policies to increase the share of solar energy use. However, the installation of conventional solar collectors is no longer so effective, therefore, various methods are being actively studied to improve the characteristics of solar collectors, which in turn leads to an increase in their performance.

Currently, a significant number of different schemes for using solar energy have been developed. The article proposes a method for using a regenerative air solar collector with increased heat transfer efficiency using hemispherical recesses as intensifiers. Testing of this

method has shown its high efficiency due to increased intensification, and the economic effect of using this method is also clearly reflected. The use of solar heating with the use of solar collectors of various types in air heating systems will significantly increase the efficiency of such systems, as well as increase the degree of replacement of traditional heat sources.

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