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Thermal Conductivity of a Vacuum Fractal Solar Collector

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Abstract- The thermal characteristic of a new type of vacuumed fractal solar collector (VFSC) is derived and evaluated in this paper. Its heating capacity is estimated based on the fractal arrangement of toroidal absorbers on a parabolic concentrator. The total coefficient of thermal losses in the VFSC is determined with minimal solar energy. At the same time, the absorbers in the VFSC are designed fractally from toroidal polymer pipes located in a vacuumed parabolic space. The possibility of working in the VFSC in non-stationary thermal modes with zero water consumption and minimal solar radiation is shown. In addition, the transmission and absorption capacity of the VFSC is estimated. The experimental results show that the use of VFSC in practice makes it possible to obtain cheap hot water at various temperatures. Also, the positive results were obtained from the helio device at low ambient temperatures in the forced mode of heating by solar radiation with zero water consumption.

Keywords Fractal solar collector, vacuumed space, polymer tube absorber, heat loss coefficient.

1. Introduction

Solar collector absorbers are one of the main elements of the solar installation design, on which both energy and economic indicators of solar heat supply systems depend [1,2]. The main advantages of solar heat collectors are high process efficiency even in subzero temperatures, ease of installation of the entire structure, anti-wind resistance of the collector and duration of operation.

Currently used absorber designs are usually realized with collectors made of expensive metals such as copper and stainless steel. This increases the cost of collectors and increases their weight. Possibilities to reduce their costs are almost exhausted. In addition, there are applications where cheaper materials such as aluminum alloy are used. The creation of structures based on the use of polymer materials [3-6] and based on nanotechnology [7-8] is a promising direction for the further development of low-temperature solar technologies. Mathematical model, thermal and economic analysis of low-cost water heater made by plastic tub have improved the design [9, 10]. One possible design of a solar water (liquid) heater is a fractal collector with an absorber made of polymer materials, made in the form of similar toroids arranged hierarchically over a plate aperture area (Fig. 1).

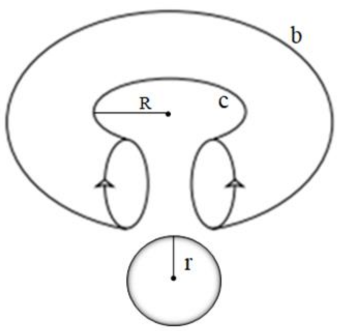


Fig 1. Troidal absorber

On the other hand, in the simplest liquid systems, ordinary water is used, which is heated directly in the collector and enters the bathroom, kitchen, etc. This model is known as "open" (or "direct") system. In regions with a cold climate, liquid collectors need to drain water in the cold season, when the temperature drops to the freezing point; or a non-freezing liquid is used as a coolant. In such systems, the liquid coolant absorbs the heat accumulated by the collector and passes through the heat exchanger. The heat exchanger is usually a water tank installed in the house, in which heat is transferred to water. This model is called a "closed system" ("indirect"). If it is necessary to prevent mixing of the heat carriers of the solar collector and, for example, a heat pump, special boilers are used. At the same time, cold weather dramatically reduces the efficiency of fractal solar collectors (FSC) [11-13]). In order to avoid such a disadvantage of the FSC, a vacuum fractal solar collector (VFSC) is proposed in this work (Fig.2).

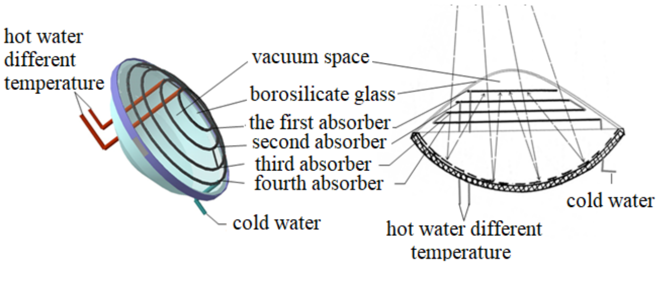


Fig 2. (a) view of the evacuated fractal solar collector, (b) split view

In the proposed structure, the aperture area is located in the evacuated space of the parabolic concentrator. In this case, the aperture area serves as a secondary energy source for absorbers, i.e., the sun rays of the fractally located absorbers reflected from the aperture area reheats fractally located toroidal absorbers. The main aim of this study is to evaluate the thermal balance of the proposed evacuated fractal solar collector.

2. Thermal Conductivity of a Vacuum Fractal Solar Collector

As it is known, the efficiency coefficient characterizes the degree of unevenness of the temperature field in the cross section of the panel or, in other words, the efficiency of the transfer of absorbed solar radiation to the coolant flow in the pipes [14-19]. It depends mainly on the panel design. At the same time, if you design these panels in the form of a parabolic concentrator and place the toroidal absorbers in the parabolic space fractally, while if you vacuum the space of the absorbers, you will get a vacuum fractal solar collector. In this case, the energy characteristics of the VFSC will be evaluated as follows.

A useful characteristic of the collector is the maximum temperature T to which the absorbing panel is heated if no heat is removed from the collector. This is the case when all the absorbed solar radiation passes into heat losses.

The coefficient of thermal losses of solar energy collectors is the main value determining the power of energy losses from the collector to the environment [5].

$$\Delta P = A \Delta \tau \, U_L \tag{1}$$

here U_L is the total heat loss coefficient of the solar collector (W/K), A is the estimated aperture area of the solar collector (m^2), $\Delta\tau$ is the duration of the heating interval of the absorber with water (s). The equation (1) shows the specific value of the heat loss coefficient, the dimension of which is W/(Km^2). According to the value of this coefficient, solar energy collectors with different designs and aperture areas can be compared. This coefficient takes into account the heat loss through the transparent, opaque collector enclosure and through the seals between them.

The determination of the reduced transmission and absorption capacity of the collector, the absorber of which is a register of polymer toroidal pipes, is of great importance for evaluating its performance. This determination is carried out on the basis of experimental data obtained with zero water consumption and a minimum temperature difference between the absorber and the environment.

The determination of the coefficient of thermal losses of a collector of such a design was considered. To calculate the normal and emergency modes of operation of solar collectors, it is necessary to know not only the above value, but also such an indicator as the reduced transmittance-absorption capacity γ [20]. This value determines the power and, accordingly, the energy absorbed by the absorber during its irradiation. Also, a computational technique for determining this product in the case of flat absorbers was considered. For absorbers of other designs, in particular, for the VFSC design considered here, both the method of experimental determination of these values and the calculated ratios should be developed individually. At the same time, the calculation methods will still be based on the use of information about the characteristics of the transmission and absorption capacity of materials used for the transparent enclosure of the collector and absorber, which are often unknown or incomplete.

To reveal the possibilities of the VFSC and ways to improve it, it is advisable to consider the energy balance equation for stationary conditions, which determines the heat capacity of the collector per unit area of the heat-receiving surface as the difference between absorbed solar radiation and heat losses to the environment.

For the stationary mode of operation of a flat collector, the power balance equation (PBE) can be written as follows:

$$\gamma I_{fsc} - U_L(t_{ab} - t_a) = GC_w(t_0 - t_i)/A \tag{2}$$

where, t_0 is the temperature of the absorber with water at the beginning of the collector heating interval by solar radiation (^0C), t_{ab} is the average over a time interval $\Delta\tau$ the value of the absorber temperature (^0C), t_a – is the ambient temperature (^0C), t_i is the water temperature at the solar collector inlet (^0C), A is the estimated area of the solar collector aperture (m^2) and G is the mass flow rate of the coolant (kg/s).

The right part of equation (2) is the useful power of the VFSC, and the left is the difference between the power absorbed by the solar energy absorber and the heat flow from it into the environment. If we enter $k = (t_{ab} - t_a)$, then for 1st fractal of the PBE the equation (3), for 2nd fractal of the PBE the equation (4), for 3rd fractal of the PBE the equation (5) and for 4th fractal of the PBE the equation (6) can be obtained for VFSC.

$$(\gamma I_{fsc} - U_L \cdot k)A_1 = G_1 \cdot C_w^1(t_0 - t_i) \tag{3}$$

$$(\gamma(I_{fsc}+Q_1) - U_L \cdot k)A_2 = G_2 C_w^2 (t_0 - t_i) \tag{4}$$

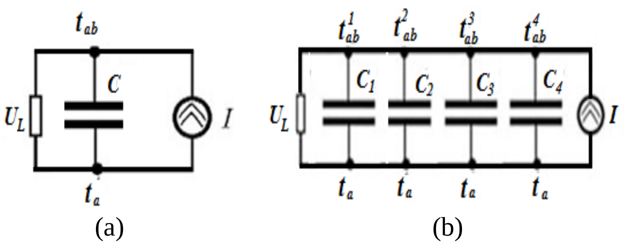
$$(\gamma(I_{fsc}+Q_1+Q_2) - U_L \cdot k)A_3 = G_3 C_w^2 (t_0 - t_i) \tag{5}$$

$$(\gamma(I_{fsc}+Q_1+Q_2+Q_3) - U_L \cdot k)A_4 = G_4 C_w^2 (t_0 - t_i) \tag{6}$$

From expression (2), the value of γ can be found if the stationary conditions of the process are met, and, of course, all the quantities necessary to solve equation (2) are known. Some of these quantities are measured or a priori known. However, all the errors associated with the inaccuracy of determining these values cause errors in determining the transmission and absorption capacity of the solar collector γ. The main contribution to the error here is due to the inaccuracy of the definition of U_L and t_{ab}.

A possible way to increase the accuracy of the determination of γ is to minimize the difference between the average temperature of the absorber and the environment during experiments. Under the condition $t_{ab} - t_a$=0, the influence of the error associated with the determination of the thermal loss coefficient of the solar collector $U_L$will also be excluded.

In connection with the above, it seems simpler to determine the transmission and absorption capacity of a solar collector based on the results of experiments performed under the condition G = 0, i.e., in a non-stationary thermal regime. Here, in contrast to the method of determining the thermal loss coefficient of the solar collector U_L, based on the use of a free transient thermal process, a forced transient thermal process with zero water consumption should be applied.



(a) (b)

Fig 3. The simplified electrothermal model of a solar collector; (a) for a flat solar collector, (b) for VFSC.

The electrothermal analogue of the solar collector in this mode is shown in Fig.3. Thus, the charging of the capacitor *C* from the current source I_{fsc} is considered in the presence of conductivity U_L. At the same time, we believe that the regular thermal regime in the system occurs immediately after the start of the solar collector irradiation process. The basis for this assumption may be that the external thermal resistance (resistance to heat transfer to the environment) is significantly greater than the internal thermal resistance due to the finite thermal conductivity of the pipe wall and its heat exchange with water.

For a solar collector with zero water consumption, the following energy balance equation can be written [21, 22].

$$\int_0^{\Delta\tau} A I_{fsc} \gamma d\tau = \int_0^{\Delta\tau} A U_L (t_{ab} - t_a) d\tau + \int_0^{\Delta\tau} m C t_{ab} d\tau \tag{7}$$

here, C is the specific heat capacity of the absorber filled with water (J/K m^2), *A* and *m* can be defined as follows,

$A = A_1 + A_2 + A_3 + A_4$

$m = m_1 + m_2 + m_3 + m_4$.

It follows from equation (7) that the value of the transmission and absorption capacity of the collector γ can be most accurately determined if we minimize the heat loss during the time Δτ and errors in averaging the values of the quantities in this interval.

If the initial value of the temperature of the absorber with water is such that $t_{ab} \approx t_a$, then the effect of energy losses at the second stage of heating, when the temperature of the absorber is higher than that of the environment, will be compensated by energy absorption at the first stage when $t_{ab} < t_a$. When preparing experiments, the value of the water temperature is calculated, which is necessary to ensure the above condition.

The thermal time constant of the collector can be determined by equation (8) and the heat capacity of the water filled absorber can be also calculated according to the well-known formula given via equation (9).

$$\tau_t = (m_1 c_1 + m_2 c_2)/U_L \tag{8}$$

$$c = m_1 c_1 + m_2 c_2 \tag{9}$$

where m_1 is the mass of the absorber (kg), m_2 is the mass of water in the absorber (kg), c_1 is the specific heat capacity of the absorber material (J/Kkg) and c_2 is the specific heat capacity of water (J/K kg).

The value of the equilibrium temperature t_m can be found from the condition of equality of the heat flux absorbed by the solar radiation absorber and the heat exchange power of the absorber with the environment:

$$t_m = t_a + \gamma I_{fsc}/U_L \tag{10}$$

Under unchanged experimental conditions (ambient temperature, solar radiation density, wind speed, etc.), the temperature of the absorber at G = 0 and U_L=const will change in time according to the following, where τ- is the current time, τ_t is the thermal time constant of the solar collector, t_m is the calculated value of the equilibrium collector temperatures, ^{0}C.

Integrating equation (7), we can obtain the average for a certain time interval Δτ value of the temperature of the absorber filled with water:

$$t_{ab} = t_i + \Delta\tau(t_m - t_i) \cdot \exp(-\Delta\tau/\tau_t)/\tau_t \tag{11}$$

3. Results and Discussion

The solar power absorbed by the fractal absorber can be calculated for different weights and specific heat capacity values of the fractal absorber. For calculation, the absorber dimensions and related constants should be known. While the absorber dimensions and related constants are given in Table 1, the weights and specific heat capacity values of the fractal absorber are given in Table 2.

Table 1. The absorber dimensions and related constants

R_1 (m)	R_2 (m)	R_3 (m)	R_4 (m)	r (m)	I (W/m^2)	I_{fsc} (W/m^2)
0.2	0.25	0.30	0.35	0.016	1400	700
A_1 (m^2)	A_2 (m^2)	A_3 (m^2)	A_4 (m^2)	γ	*UL* (*W/K*)	*R* (*m*)
0.13	0.16	0.19	0.22	0.137	0.33	0.4
t_0 (^0C)			t_a (^0C)		$-\tau$ (s)	
35			20		16	

Table 2. Weight and specific heat capacity of each absorber

	m_1	m_2	c_1	c_2
Absorber 1	1.46	0.10	2.09	4200
Absorber 2	1.82	0.126	2.09	4200
Absorber 3	2,18	0.151	2.09	4200
Absorber 4	2,54	0.176	2.09	4200

The absorbed solar power by the first fractal absorber can be calculated by using equation (12). For this situation we need R_1, r and A_1.

$$(\gamma I_{fsc} - U_L \cdot k)A_1 = G_1 \cdot C_w^1 (t_0 - t_i) \quad (12)$$

here k = ($t_{ab} - t_a$), t_{ab} is the average for the time interval is calculated from equation (11), the value of the equilibrium temperature t_m is found from equation (10) as follows.

$$t_m = t_a + \gamma I_{fsc} / U_L = 20 + 0.137 * 700/0.33 = 42.45 \text{ ℃}$$

The thermal time constant of the collector given by the equation (8) can also been calculated as follows.

$$\tau_t = (m_1 c_1 + m_2 c_2)/U_L = (1.46 * 2.09 + 0.100 * 4200)/0.33 = 1281.96 \text{ s}$$

Then, we can find t_{ab} and the average for the time interval by using the equation (11) as given below.

$t_{ab} = t_0 + (t_m - t_0)[1-\exp(\frac{-\tau}{\tau_t})]$=35+(42.45-35)|1-exp(-16/1281.96)=35.149 ^0C

$k = (t_{ab} - t_a)$=(35.149-20)=15.149 ^0C

After finding all necessities, the absorbed solar power by the first fractal absorber can be calculated as given below.

$Q_1 = (\gamma I_{fsc} - U_L \cdot k)A_1$=(0.137*700-0.33*15.149)*0.13=11.8 W

By using the same procedure given above the absorbed solar power by the second, third and fourth fractals can be calculated. R_2 and A_2 are used for the second fractal, while R_3 and A_3 are used for the third fractal. The fourth fractal calculations need R_4 and A_4.

For the second fractal absorber;

$(\gamma(I_{fsc} + Q_1) - U_L \cdot k) A_2 = G_2 C_w^2 (t_0 - t_i)$

$\tau_t = (m_1 c_1 + m_2 c_2)/U_L$=(1.82*2.09+0.126*4200)/0.33= 1615,15 s.

$t_m = t_a + \gamma I_{fsc}/U_L$=20+0.137*700/0.33=42.45 ^0C.

$t_{ab} = t_0 + (t_m - t_0)[1-\exp(\frac{-\tau}{\tau_t})]$=35+(42.45-35)|1-exp(-16/1615,15)=35.0745 ^0C

$k = (t_{ab} - t_a)$=(35.0745-20)=15.0745 ^0C

$Q_2 = (\gamma(I_{fsc} + Q_1) - U_L \cdot k)A_2$=(0.137*(700+11.8)-0.33*15.0745)*0.16=14.8 W

For the third fractal absorber;

$(\gamma(I_{fsc} + Q_1 + Q_2) - U_L \cdot k)A_3 = G_3 C_w^2 (t_0 - t_i)$

$\tau_t = (m_1 c_1 + m_2 c_2)/U_L$=(2,18*2.09+0.151*4200)/0.33= 1935,6 s.

$t_m = t_a + \gamma I_{fsc}/U_L$=20+0.137*700/0.33=42.45 ^0C.

$t_{ab} = t_0 + (t_m - t_0)[1-\exp(\frac{-\tau}{\tau_t})]$=35+(42.45-35)|1-exp(-16/1935,6)=35.0745 ^0C

$k = (t_{ab} - t_a)$=(35.0745-20)=15.0745 ^0C

$Q_3 = (\gamma(I_{fsc} + Q_1 + Q_2) - U_L \cdot k)A_3$=(0.137*(700+11.8+14.8)-0.33*15.0745)*0.19=17.96 W

For the fourth fractal absorber;

$(\gamma(I_{fsc} + Q_1 + Q_2 + Q_3) - U_L \cdot k)A_4 = G_3 C_w^2 (t_0 - t_i)$

$\tau_t = (m_1 c_1 + m_2 c_2)/U_L$=(2,54*2.09+0.176*4200)/0.33= 2256,06 s.

$t_m = t_a + \gamma I_{fsc}/U_L$=20+0.137*700/0.33=42.45 ^0C.

$t_{ab} = t_0 + (t_m - t_0)[1-\exp(\frac{-\tau}{\tau_t})]$=35+(42.45-35)|1-exp(-16/2256,06)=35.0745 ^0C

$k = (t_{ab} - t_a)$=(35.0745-20)=15.0745 ^0C

$Q_4 = (\gamma(I_{fsc} + Q_1 + Q_2 + Q_3) - U_L \cdot k)A_4$ =(0.137*(700+11.8+14.8+17,96) - 0.33*15.0745)*0.22=21,3 W

Now we can calculate the total absorbed solar power in the EFSC. We also need calculation of reflected solar power from the aperture area of a parabolic concentrator. For this we should calculate total area of toroidal fractal absorbers, aperture area of the parabolic concentrator, aperture area of reflected sunlight and the reflected solar insolation as given below.

$A = A_1 + A_2 + A_3 + A_4$ =0,13+0,16+0,19+0,22=0,7 m^2

Aperture area of the parabolic concentrator is;

$$A_{par} = \frac{4\pi R^2}{2} = \frac{4*3.14*0.4^2}{2} = 1\ m^2$$

Aperture area of reflected sunlight is;

$$A_{ref} = A_{par} - A = 1 - 0.7 = 0.3\ m^2$$

Reflected solar insolation is:

$$I_{ref} = IA_{ref} = 1400 * 0.3 = 420\ W/m^2$$

By using calculations determined above the reflected power absorbing by the first fractal toroidal absorber and the total absorbing power ($Q_{f\text{-}total}$) in VFSC can be calculated as follows.

$Q_0 = (\gamma I_{ref} - U_L \cdot k)A_1 = (0,137*420 - 0.33*15.075)*0,13 = 6.83\ W$

$Q_{f\text{-}total} = (Q_1+Q_0)+Q_2+Q_3+Q_4 = (11.8+6.83)+14.8+17.96+21.3 = 72.69W$

As can be understood from the calculations given above, the power value obtained from the sun depends on the solar radiation intensity. The intensity of the sun's depends on the distance of the sun. The relation of the solar intensity with the sun's distance given in Table 3 is drawn Fig. 4.

Table 3. The dependence of the intensity of the sun on its height h_s

I (W/m²)	100	300	550	710	780	810
h_s (deg)	0.1	0.16	0.31	0.47	0.63	0.79
I (W/m²)	840	870	885	895	900	
h_s (deg)	0.94	1.1	1.26	1.41	1.57	

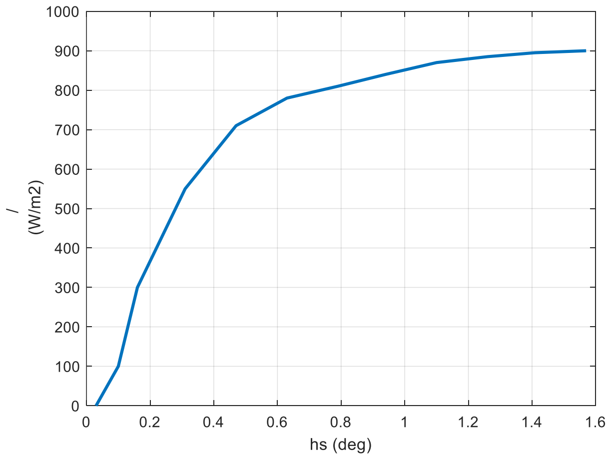


Fig 4. The dependence of solar intensity on the height of the sun.

Since the height of the sun depends on the time of day and on the day of the year, from here we can obtain the dependence I(t) for each day. In formula (2), the value of *I(t) cosi* is the intensity of incident solar radiation. The value of angle *i* also depends on time. Using these properties of solar radiation, let's present the results of the VFSC experiment, the graph (Fig. 5), which is obtained from Table 4, shows the dependence of the amount of solar power accumulated by VFSC. It can be seen that the amount of solar power depends on angle. The power produced does not increase as the angle increases. The power varies according to different values of the angle.

Table 4. The dependence of the amount of solar power accumulated by VFSC

Q (W)	100	86	80	83	92
α (deg)	0	20	40	60	80
Q (W)	106	113	115	109	99
α (deg)	100	120	130	160	180

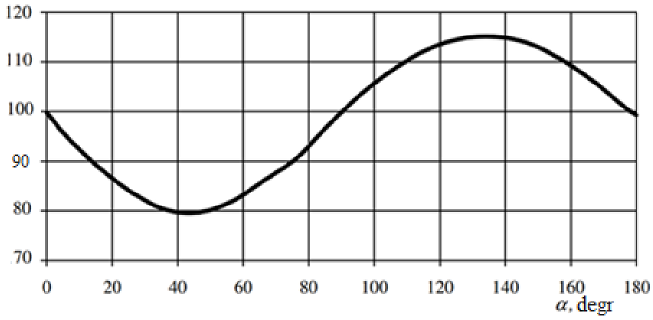


Fig 5. The dependence of the amount of solar power accumulated by VFSC.

To compare the absorbing power of the VFSC with the absorbing power of the EFSC, we calculate the absorbed power of a flat solar collector. At the same time, the absorption areas of these collectors are the same. Since the sum of the four areas used for the VFSC is 0.7m², we took the area as 0.7m² for the EFSC system.

From equation (2) the absorbing power of a flat collector:

$Q_{flat} = (\gamma I - U_L k)A = (0.137*700 - 0.33*15.075)*0.7 = 63.65W$

While calculating the total absorbing power ($Q_{f\text{-}total}$) in VFSC as 72,69W, this value ($Q_{f\text{-}total}$) was calculated as 63,65W for the EFSC. When the two power values are compared, it is seen that 5,8% more power is obtained with VFSC.

4. Conclusion

The thermal characteristic of a new type of vacuumed fractal solar collector (VFSC) was derived and evaluated in this study. The total coefficient of thermal losses in the VFSC was determined with minimal solar energy. At the same time, the absorbers in the VFSC were designed fractally from toroidal polymer pipes located in a vacuumed parabolic space.

A solar water heater with fractally arranged toroidal absorbers on a parabolic concentrator provides greater and more uniform generation of useful energy throughout the year than other solar heaters without such a design. This is due to the fact that on the VFSC, subsequent fractal toroidal absorbers, in addition to the first, will be secondary energy emitters for subsequent toroidal absorbers in the opposite direction, the flesh up to the first being at the focus of the parabolic concentrator.

The methodological basis for determining the transmittance - absorption capacity in the VFSC based on the power balance equation in the solar radiation heating mode with zero water consumption was considered. The tests were carried out under suitable external conditions for the stability of solar radiation and ambient temperature. It is also important that in order to reduce the impact of the inaccuracy of knowledge of the heat loss coefficient in the VFSC, the absorber is filled with water at a temperature lower than the ambient temperature at which experiments are supposed to be carried out.

Energy indicators in the VFSC, as well as the maximum water temperature, significantly depend on the size of fractal absorbers. In the spring and autumn period, to heat water to higher temperatures, it is necessary to reduce the specific load on water (the thickness of the water layer), which requires an increase in the absorption area to ensure the desired flow of hot water, or the use of an additional heater.

The experiments and calculations carried out showed the advantages of the VFSC compared to the flat collector. Further methodological developments and research will be related to the optimization of modes and sizes of purely solar and combined hot water systems consisting of solar water heaters and traditional heat sources.

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