# The analysis of exploitation possibility of thermal solar plants depending on specific of climate conditions of territory

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**Abstract.** In article the review of standard structures and technical solutions of thermal solar power plants of hot water supply is made, and also methods of increase of level of automation and efficiency of their functioning are offered. The conclusion about opportunities of operation and efficiency of use depending on power indicators, geographical and climatic conditions of the district is made.

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## Introduction

There is a large number of the solar power installations differing depending on a configuration of system, ways of recirculation of the heat carrier, the principles of operation of regulators, etc. The analysis of literature allowed to allocate standard structures of solar power installations and the main schemes of management with them [1, 2, 3], and also to estimate efficiency and expediency of operation taking into account specifics of climatic conditions of a certain district. The main power indicators of overall performance of solar power installation are:

1. efficiency of generation of thermal energy by solar collector due to sunlight absorption;
2. efficiency of process of charging of storage container of thermal energy.

## Main part

The main power indicator of efficiency of a production cycle of a solar collector is the efficiency coefficient (EC) $\eta_{SC}$ of its thermal cycle [1] which can be determined by a formula (1).

$$\eta_{SC} = \frac{N_{SC}^{help}}{N_{\Sigma}^{SA} S_{SC}}, \qquad (1)$$

where $\eta_{SC}$ – the useful heating capacity of a solar collector, W; $N_{\Sigma}^{SA}$ - power of the sunlight arriving on a reception platform in the form of a solar collector, randomly focused in space, W/m$^2$; $S_{SC}$ - area of a ray absorbing surface of a solar collector.

$$N_{CK}^{help} = N_{\Sigma}^{CK}\alpha\tau - \Delta N_{CK}(T_{CK} - T_{OC}), \qquad (2)$$

where $N_{\Sigma}^{CK}$ - power of solar radiation reaching the surface of the solar collector; $\tau$ - bandwidth transparent insulation collector; $\alpha$ - absorptive capacity of the absorber; $\Delta N_{CK}$ - thermal loss in the solar collector; $T_{CK}$ - temperature of the coolant in the reservoir, K; $T_{OC}$ - ambient temperature, K.

$$N_{CK}^{help} = mC_p(T_2 - T_1), \qquad (3)$$

$$\eta_{CK} = K_{\Pi}\alpha\tau - \Delta N_{CK}\frac{(\overline{T_{CK}} - \overline{T_{OC}})}{N_{\Sigma}^{CH} S_{CK}} =$$

$$= \eta_0 - \Delta N_{CK} f_{CK}(T_{CK}, T_{OC}, N_{\Sigma}^{CH}, S_{CK}).$$

*(4)*

where $\eta_0$ – effective optical efficiency solar collector.

At change of power of the sunlight arriving on a reception platform in the form of a solar collector, randomly focused in space $N_{\Sigma}^{SA}$ from 300 to 1000 W/m$^2$ the efficiency coefficient increases from 32% to 59%. At increase of ambient temperature, the efficiency also increases due to reduction of absolute value of the second composed in expression (4). Efficiency coefficient of solar plants significantly depends on an absorber material. With increase in coefficient of heat conductivity of a material of which the absorber is made, absorbing ability of an absorber $\alpha$ and, as a result from (2), the efficiency coefficient increases. So, for material thickness in 1 mm from copper, aluminum, steel and plasticity with coefficients of heat conductivity of 390, 205, 45 and 0,6 W / m2·ºC, efficiency of a collector makes 52, 50, 48 and 22% accordingly [1].

Management of process of charging discharge of a storage container of thermal energy is the important factor influencing productivity of system as a whole and efficiency of a solar collector in particular. On the basis of dependences (1) and (3), the efficiency coefficient increases at decrease in temperature on an entrance of a solar collector which corresponds to the output temperature of the heat carrier from heat storage container. Therefore, management of heat exchange process in a peak operating mode (a power source operating mode with a variable power for ensuring needs of consumers) – a regime of thermolysis directly influences efficiency coefficient of solar collector and defines overall performance of system as a whole.

The simplest hot water supply of the consumer using for heating renewables is single-loop system of heating of water with natural recirculation of the heat carrier (see Fig.1). The contour of the heat carrier and hot water supply contour in solar power plants of this kind structurally aren't divided. Water from the lower part of a storage container 3 with a temperature $T_1$ through bringing pipe 4 arrives in a solar collector 1. Water, heated in solar plants under the influence of sunlight with a temperature $T_2$ comes back on taking-away pipeline 2 in a tank. Natural current of water in power installation is created at the expense of a difference of pressure in the system caused by different density of water in the top and lower part of a collector:

$$\Delta p = g\Delta H(\rho_1 - \rho_2),$$

where $g$ – acceleration of gravity, 9,81 m/s$^2$; $\Delta H$ – difference of high-rise marks in an input of hot water in a storage container and on an input of cold water in the lower part of a tank, m; $\rho_1$ and $\rho_2$ – density of cold water corresponding to temperature $T_1$ and on input of hot water in a storage container of the corresponding temperature $T_2$, kg/m3.

The more the difference of temperatures $T_1$ and $T_2$ and heights $\Delta H$, there is higher intensity of natural recirculation in power installation. Besides, a compulsory condition of functioning of system is excess of tank bottom mark over top part mark of solar plants. Otherwise, the process of the return recirculation of the heat carrier in the absence of solar activity is possible. Power installations of considered type gained rather wide circulation around the world in the countries with hot climate [1, 2, 4]. The main advantage of such systems is the low cost and independence of additional power sources. Installations are autonomous non-volatile hot water supply without automation of process of regulation of temperature. Considered solar power plants gained big distribution in agriculture, in a life for preparation of hot water for production and technological needs.

Increase of efficiency of functioning of hot water supply with application of passive solar power installations probably generally due to introduction of constructive changes as directly in a solar collector, and in system as a whole, and also due to use of the additional heat exchange equipment and locking regulating fittings. Automation of management by thermal processes in such systems conducts to increase in their cost, and also to loss of independence of functioning from traditional power sources. Systems with natural recirculation of the heat carrier are, as a rule, used at rather small consumption of hot water, for example, for domestic needs. For hot water supply systems at big fences of water it is more effective to use power installations with compulsory recirculation of the heat carrier (a solar power plant of active type), their fundamental difference is existence of the pump of compulsory giving of the heat carrier in a solar collector. The function chart of the elementary active single-circuit solar power installation is presented in Fig.2. [5]

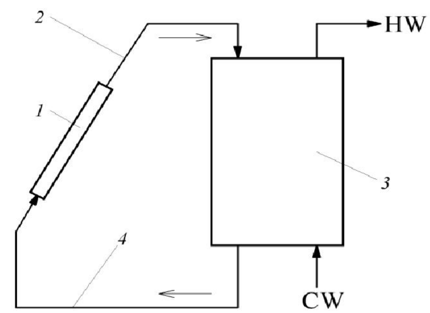


**Fig.1. Functional scheme of thermal solar plants with natural circulation of heat carrier:**
1 – solar collector ; 2 – discharge pipe; 3 – direct cylinder of heat energy; 4 – inlet pipe of cold water; CW – cold water; HW– hot water.

As well as in the system presented in Fig.1, the scheme is single-circuit and has no constructive division on the heat carrier channel. For control of the pump in order to avoid process of cooling of the heat carrier in the absence of sufficient level of sunlight in systems regulators of a difference of temperatures 1c. The regulator 1c on the basis of information from temperature sensors in a boiler or on a bringing pipe and heat carrier temperatures in a solar collector forms an operating signal on the relay 1d of the electric motor of the pump 1e. As a rule, in the specified systems, on-off regulators of a difference of temperatures having a simple design and low cost are used. The thermostatic mixing valve 6 is the regulator of direct action 2a and carries out regulation of temperature of hot water due to change of volume expenses of heated and cold water. Installations of this type weren't widely adopted at the expense of rather high cost due to use of volatile automatic equipment from the electric power, increase in complexity of a design and, as a result, decrease in reliability at rather low indicators of power efficiency. These installations are, as a rule, applied to heating of swimming pools, in agriculture – where heated water is used for technological needs. Often, the energy tank accumulator is expelled from structure of the system, because a swimming-pool itself can make this function.

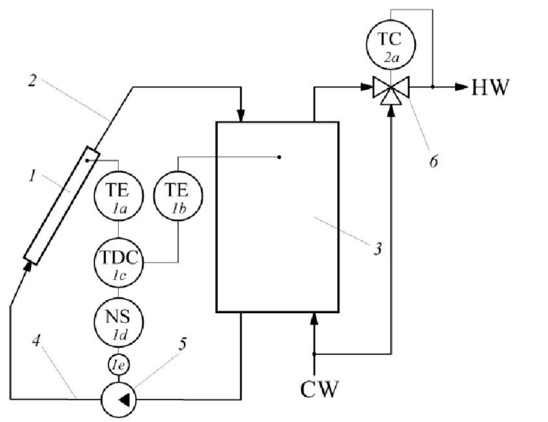


**Fig.2. Functional scheme of active thermal solar plants:**
1 - solar plants (solar collector); 2 – discharge pipe; 3 – direct cylinder of heat energy; 4 – inlet pipe of cold water; 5 – recirculating pump; 6 – thermostatic mixing valve; CW – cold water; HW – hot water; 1a, 1b – temperature sensors; 1c – regulator of a difference of temperatures; 1d – electromagnetic relay or magnetic starter или; 1e – pump electric motor; 2a – regulator of temperature of direct action.

In this work [6] authors offer the modification of considered structure consisting in replacement of a volatile control system of the pump on photo-electric system of regulation in which the electric motor of the pump is put in action by the energy dependent on intensity of sunlight, received by photo-electric elements. Disadvantage of the approach is essential rise in installation price and range narrowing of application in the conditions of colder climate.

In the conditions of colder climate (at decrease in temperature of external air is lower 0) double-circuit active schemes of solar power plants are applied to an exception of freezing of the heat carrier at weak solar activity and low ambient temperature (see Fig.3) with division of contours of circulation of the heat carrier and the water, to the arriving consumer. As the main heat carrier heated in solar plants, chemically active nonfreezing liquid (antifreeze, water mix with ethylene or propylene, glysantin, etc.) [1, 2, 7, 8] is used. The functional scheme of automation of solar power installations of such kind is presented in figure 5.

Fundamental difference of considered type of systems consists of available heat exchanger 7. Additional benefit of the double-circuit scheme is section of fresh hot water which is used for economic domestic needs, from the nonfreezing heat carrier in the solar collector (solar plants), containing toxic substances.

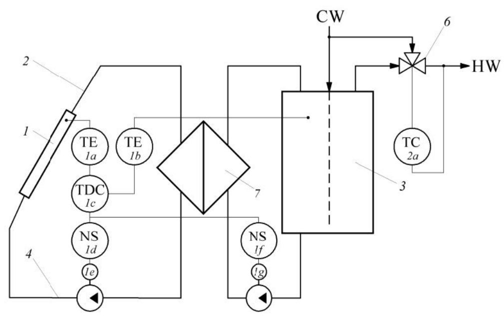


**Fig. 3. The functional chart of an active dual-circuit thermal solar plant with external heat exchanger:**
1 - solar collector; 2 – discharge pipe; 3 – thermal energy storage container; 4 – cold water supply pipe; 5 – recirculating pumps; 6 – temperature blending valve; 7 – heat-exchanger; CW – cold water; HW – hot water; 1a, 1b – temperature sensors; 1c – temperature difference controller; 1d, 1f – electromagnetic relay or magnetic starter; 1e, 1g – electric motor of the pump; 2a – direct-action temperature controller.

The power feed of heating agent into the solar collector is done with pump 5, activated by electric motor 1e at the contact closure of electromagnetic relay 1d at the signal of temperature difference controller 1c. The controller 1в generates a signal to turn on electric motors 1e and 1g of heat agent power feed pumps on the basis of comparing the temperature of heating agent in SC (temperature sensor 1a) and the temperature of water, prepared by the power plant, (sensor 1b) to avoid the process of reverse heat exchange between hot water and heating agent at the low values of environmental temperature and insolation. As in the previous case, the temperature blending valve 6 regulates the temperature of hot water by changing the volume flow rate of heated and cold water. But the relatively low temperature of water, obtained in such systems, not always meets the consumers' needs due to the necessity of achieving the higher heating effect and efficiency coefficient of the system, which is not always possible in the external climatic conditions. So, on the basis of international practices, according to which it is reasonable to satisfy no more than 80% of need in hot water, the solar thermal plants of this type usually include the additional water heating system (AWH) on the base of supplementary power sources (SPS) [**Error! Reference source not found.**, **Error! Reference source not found.**]. The functional charts of systems of this type are shown in figures **Error! Reference source not found.**.

The system has two control channels: of heat and mass transfer in SC-storage container circuit and of supplementary power source circuit. Controlling the process of charging the thermal energy storage container is done by the above-mentioned standard pattern of temperature difference. In the additional water heating circuit the set-point temperature of hot water is maintained with a controller 3b by a signal of temperature sensor 3a by means of controlling the electromagnetic valve 3d. The necessity of using a temperature blending valve 6 in many cases is eliminated. There are two main types of the considered systems, which differ with the positioning of the heat exchanger of additional water heating from supplementary power source. The simplicity of design at using the heat exchanger of additional water heating inside the thermal energy storage container creates certain differences in the context of controlling thermal processes in the plant, and complicates the design of thermal energy storage container. The similar systems are presented in works [**Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**]. Heat exchangers in the container can consist of several parts to implement the controlled process of heating of various capacities.

The units (Fig.3, Fig.4) have become widely used in the world both in the household sphere, and in industry. System, the functional charts of which is shown in figures **Error! Reference source not found.**, are the most advisable in terms of correlation between cost characteristics and performance measurements and are the most widely-spread.

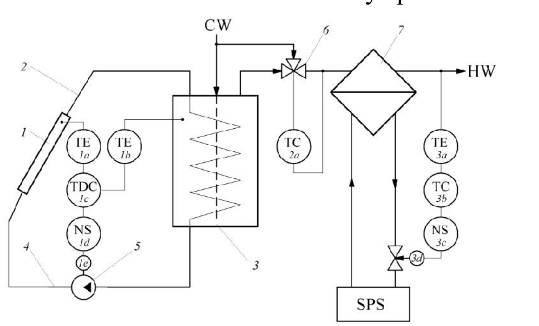


**Fig.4. The functional chart of an active dual-circuit thermal solar plant with a series-connected supplementary power source:**
1 – solar collector; 2 – discharge pipe; 3 – thermal energy storage container; 4 – cold water supply pipe; 5 – recirculating pumps; 6 – temperature blending valve; 7 – heat-exchanger; CW – cold water; HW – hot water; SPS – supplementary power source; 1a, 1b – temperature sensors; 1c – temperature difference controller; 1d – electromagnetic relay or magnetic starter; 1e – electric motor of the pump; 2a – direct-action temperature controller; 3a – temperature sensor; 3b – temperature controller; 3c – electromagnetic relay; 3d – electric drive of the valve.

It should be pointed out, that one of the most widespread methods of improving the efficiency of solar power unit is using the SC positioning system with follow-up motor. The considered approach can be applied to all types of systems in question (Fig.1 – Fig.4. But due to the complexity of design and increasing of the overall cost of the system, depending on local climatic conditions, is not always feasible.

In the world, the most widespread approach of improving the efficiency of energy supply systems is the application of solar power plants along with other non-conventional energy sources [1, **Error! Reference source not found.**, 7-**Error! Reference source not found.**]. In conditions of colder climate, for example, moderately continental, the application of wind-driven and photoelectrical equipment, sources, using the groundwater energy, heat pumps is economically unviable – at the substantial appreciation and structural complicating of the system, the sources mentioned have low operational performance and, as a consequence, the payback period of such systems exceed their service life.

To assess the opportunities and applicability of a certain structure and controlling system of solar power plants in buildings' hot-water supply systems, and to select their functional units, it is necessary to evaluate the energy performance indicators and cost performance of system's units.

On the basis of formula (1) the energy characteristic of solar collector can be shown in the form of functional relation (**Error! Reference source not found.**) [**Error! Reference source not found.**]

$$\eta_{SC} = F_{SC}\left(X, \Delta T, \Delta N_{SC}, N_{\Sigma}^{SA}, S_{SC}\right) = \eta_0(X) - \Delta N_{SC}(X) f_{SC}\left(\Delta T, N_{\Sigma}^{SA}, S_{SC}\right), \quad (5)$$

where $X$ - the general parameter vector, describing the design peculiarities of the solar collector;

$\Delta T$ - corresponds to the temperature difference $T_{SC}$ and $T_{OC}$.

The peculiarities of the design influence considerably the efficiency coefficient. So, the transparent insulation of SC with one- or two-layer glazing reduces the total heat loss, but increases the solar radiation loss due to pass-band reduce, i.e. reduces $\eta_0$ and $\Delta N_{SC}$. The values of these parameters depending on SC design are shown in table Table 1.[**Error! Reference source not found.**].

In the graphical interpretation the relations $\eta_{SC}(X, \Delta T, \Delta N_{CK}, S_{SC})$ are shown in figure Fig.5 for $S_{SC} \equiv 1м^2$ and collectors' structures, described in table Table 1. The arrows in the drawing show the calculation sequence of solar collector efficiency coefficient, which amounts to 50%, at the difference $\Delta T = 40°C$ for hot water supply of consumers at $N_{\Sigma}^{SA} = 500$ Вт/м$^2$ for the selective flat collector with one-layer glazing. At the increase of $N_{\Sigma}^{SA}$ to $1000$ Вт/м$^2$ (which can be conducted by concentrators of solar radiation in the SC design), the efficiency coefficient increases by 5%.

**Table 1. The influence of the SC design on its energy indicators**

| Type of SC | Construction of SC | $\eta_0$ | $\Delta N_{CK}$ |
|---|---|---|---|
| 1 | Flat SC without glazing | 0,95 | 15,0 |
| 2 | Flat SC with one-layer glazing | 0,85 | 7,0 |
| 3 | Flat SC with two-layer glazing | 0,75 | 5,0 |
| 4 | SC with selective coating for heat-absorbing surface and one-layer glazing | 0,80 | 3,5 |
| 5 | Vacuumized glass tube SC | 0,75 | 2,0 |

The efficiency coefficient is substantially influenced by the values of functional relation $f_{SC}(\Delta T, N_{\Sigma}^{SA}, S_{SC})$, °C · м$^2$/Вт. At small values, when $f_{SC} < 0{,}013$ °C · м$^2$/Вт, the maximum efficiency coefficient is demonstrated by flat solar collector without glazing, providing the slight temperature drop $\Delta T \leq 15°C$. In the range $0{,}013$ °C · м$^2$/Вт $\leq f_{SC} < 0{,}045$ °C · м$^2$/Вт the flat solar collector with one-layer glazing is more efficient, than with two-layer glazing. For $f_{SC} \geq 0{,}025$ °C · м$^2$/Вт the best advantages has the vacuumized glass tube collector [**Error! Reference source not found.**].

In summer time at the high outdoor temperature and high solar activity the flat solar collectors without glazing are the most productive for heating. In the figure there are shown the promising zones of the flat collectors' effective use:

1) $f_{SC} \leq 0{,}03$ °C · м$^2$/Вт (zone A) – heating of swimming pools;

2) $0{,}03$ °C · м$^2$/Вт $< f_{SC} \leq 0{,}08$ °C · м$^2$/Вт (zone Б) – using SC for hot water supply systems;

3) $f_{SC} > 0{,}08$ °C · м$^2$/Вт (zone B) – effective use of solar collectors for the heating of buildings.

From (4) follows, that the efficiency coefficient depends considerably on the degree of insolation in a day and throughout a year, which is most noticeable with account of sinusoidal pattern of solar insulation power alteration in time. The effectiveness of collector functioning reduces significantly in cold season at the low solar activity and air temperature.

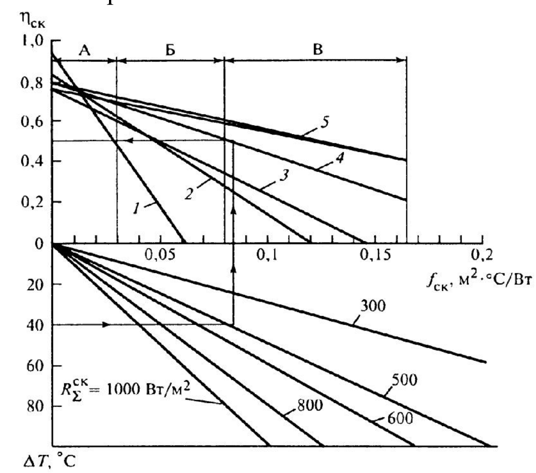


**Fig. 5. The energy characteristics of solar collectors:**

1 – collector without glazing; 2 – collector with one-layer glazing; 3 - collector with two-layer glazing; 4 - selective flat collector with one-layer glazing; 5 - vacuumized glass tube collector.

Analysis of solar collector's energy characteristics to assess the possibility of its application in solar power plants depending on functional purpose and environmental conditions in Fig.6 there are shown the ultimate values $N_{\Sigma}^{SA}$ depending on temperature difference $\Delta T$, at which the efficiency coefficient is constant $\eta_{CK}$=0%, and the ultimate values $N_{\Sigma}^{SA}$ depending on temperature difference $\Delta T$, at which the efficiency coefficient is constant $\eta_{SC}$= 50% respectively.

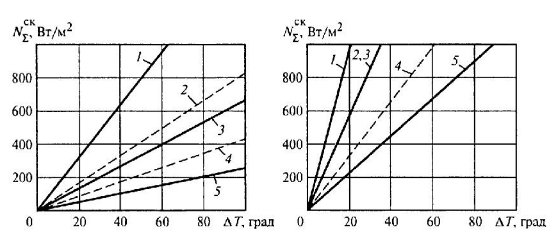

**Fig. 6. Dependence of $N_{\Sigma}^{CK}$ on $\Delta T$ at $\eta_{CK}$ = 0% (a) and $\eta_{CK}$ = 50% (б) for various types of solar collectors:**
1 – collector without glazing; 2 – collector with one-layer glazing; 3 - collector with two-layer glazing; 4 - selective flat collector with one-layer glazing; 5 - vacuumized glass tube collector.

Usually for the hot-water supply the difference $\Delta T$, altering within the range 20..50°C, is required. So, for the temperate zone of Russia with solar power on the surface of solar collector $N_{\Sigma}^{SA}$, no more than 300..500 W/m$^2$ it is preferable to use selective flat collector with one-layer glazing or vacuumized glass tube collector in heat solar plants [**Error! Reference source not found.**]. As the application of the latter is hampered due to high cost parameters, the optimal variant in terms of correlation between energy performance factors and cost parameters is the fourth type of solar collectors. Besides, it is simple design significantly contributes to the reliability of system.

**Conclusions**

So, the choice of power plants structure and their controlling systems is done on the base of analyzing the local climatic conditions. The main indicator of solar power plant performance is the efficiency coefficient. The determining factor of selecting is the correlation of performance indicators, presented as the absolute values of the saved energy resources costs and the costs of implementation measures.

We can make a conclusion about reasonability of using in conditions of moderate continental climate the solar power plants with forced heat-agent recirculation and flat solar collectors with selective coating and one-layer glazing in systems of heat water supply systems of the buildings. Besides, due to peculiarities of meteorologic conditions the solar power plant can't satisfy the 80% of the total requirements in hot water (excluding summer time) and, as a result, can't exercise functions of single heat source. So the function charts in figures 1 can't be used effectively in conditions of moderate continental climate. The most advisable are variants of systems, the structures of which are presented in figures Fig.4. In the given schemes the backup power source provides the additional water heating. In conditions of moderate continental climate it is advisable to use the additional power source, capable to provide the full thermal load, i.e. as the main heat source, and the solar power plant – as an additional source, operating at peak load, which is going to allow raising considerably the energy efficiency of the buildings' hot water supply.

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