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EFFICIENCY OF USE OF A HYBRID SOLAR COLLECTOR

В.В. Височин, Н.А. Верстак. **Ефективність використання гібридного сонячного колектора.** Проведено числові дослідження гібридного сонячного колектора (ГСК) при виробництві електричної й теплової енергії. Математична модель дозволяє проаналізувати режимні параметри ГСК – температуру нагрівання й продуктивність залежно від зовнішніх умов і вплив температурного режиму на показники роботи ГСК. Мета роботи – визначення раціональних температурних режимів роботи гібридного сонячного колектора з урахуванням ефективної електро- і теплопродуктивності. Методом дослідження є створення й аналіз комплексної математичної моделі гібридного сонячного колектора для реальних умов динамічної сонячної й кліматичної ситуації. Показано, що найбільшу прибутковість має варіант із температурою абсорбера 20 °C і тепловим насосом. Не набагато нижче дохід від експлуатації у варіанті з комбінованими температурними режимами (20/35) °C, який з технічної точки зору є найбільш доцільним. Варіант із температурою абсорбера 50 ºC, у якому не використовується тепловий насос, програє всім іншим схемам з відводом тепла. Найнижчою прибутковістю відрізняється варіант «без охолодження абсорбера». Визначена необхідність підтримки температури абсорбера на рівні 20…35 °C з використанням трансформатора тепла за умовами ефективної експлуатації при стійкому задоволенні потреб в електричній і тепловій енергії з позитивним технічним і економічним ефектом. Запропоновано здійснювати диференційований температурний режим роботи ГСК на різних рівнях у літній (35 °C) і зимовий (20 °C) час. Запропоновано математичну модель для опису температурного режиму роботи гібридного сонячного колектора в умовах примусового охолодження. Дані обґрунтовані рекомендації з ведення режиму роботи гібридного сонячного колектора, сполученого з тепловим насосом, при цілорічній експлуатації.

Ключові слова: гібридний сонячний колектор, геліосистема з тепловим насосом, температурний режим

V. Wysochin, N. Verstak. **Efficiency of use of a hybrid solar collector .** Numerical researches of a hybrid solar collector (HSC) at electric and thermal energy generation are conducted. Mathematical model allows to analyse operating parameters of a HSC – heating temperature and productivity depending on external conditions and influence of a thermal mode on indicators of HSC work. The purpose of the study – identification of rational thermal operating modes of a hybrid solar collector taking into account effective electrical and heating capacity. The research method consisted in creation and analysis of complex mathematical model of a hybrid solar collector under real conditions of a dynamic solar and climatic situation. It is shown that the greatest profitability possesses the variant with absorber temperature of 20 °C and a thermal pump. Slightly lower is the profit of using combined thermal modes (20/35) °C, which from the technical point of view is the most efficient one. The 50 ºC alternative, in which the thermal pump is not used, loses to other designs with heat removal. The lowest profitability is in the “without absorber cooling” alternative. Necessity of maintenance of absorber temperature at the level of 20…35 °C is shown, using the transformer of heat on conditions of effective operation at stable satisfaction of needs in electric and thermal energy with positive technical and economic effect. It is offered to operate in a differentiated thermal operating mode of HSC at different levels in the summer (35 °C) and winter (20 °C) time. The mathematical model for the description of a thermal operating mode of a hybrid solar collector in the conditions of forced cooling is proposed. Well-founded recommendations about conducting an operating mode of the hybrid solar collector interfaced to the thermal pump at year-round operation are made.

Keywords: hybrid solar collector, solar system with thermal pump, thermal mode

Introduction. Efficiency of a traditional photovoltaic module falls at temperature growth, electric power productivity decreases especially sharply when surface temperature of a photo cell is above 50 °C [1], which often takes place in summertime. This problem can be solved by integration of photovoltaic panels and solar collectors for thermal energy development into one technological device [1 – 3]. In such a module photovoltaic elements are cooled by means of active heat removal system using liquid heat-carrier through the channels built in a back of the panel. Thus, that part of thermal

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energy, which is traditionally lost in environment and therefore reduces system effectiveness, in a case with a hybrid solar collector can be utilized.

Analysis of recent research and publications. Electrogenerating efficiency of a hybrid solar collector (HSC) essentially depends on temperature of absorber [1, 4]. With growth of temperature the efficiency coefficient of the module decreases. Therefore the working temperature should be low, which is necessary to consider while choosing operating modes of modules [3]. In order to maintain the temperature of the panel at required level forced heat-carrier circulation is performed, therefore control process is simplified, but at the same time part of the generated electric power is spent on pump operation [3]. There is a serious contradiction in a combined device of this kind, which consists in essentially opposite requirements towards the level of temperature for generation of electric and heat energy. In this regard there was an alternative decision supposing work of the module at low temperatures with high efficiency coefficient of power generation, and for consumers of heat the heat-carrier temperature is specially raised in the second stage of the system [5, 6].

The choice of HSC thermal operating modes was carried out by a number of authors. In [5], for example, it is offered to choose thermal operating mode of HSC according to loading priority: for mainly heat consumers – a high thermal mode, for mainly electric power consumers – a low one. However the choice of modes is insufficiently proved. Researches, as a rule, are done on analytical models. Models differ in depth of object description. Thus limitation of mathematical description takes place, mainly it can be seen in detailed description of the objects working in interfaced and essentially non-stationary conditions. Thus it is not possible to make a choice of effective thermal operating modes of HSC taking into account heat and electric productivity at simultaneous satisfaction of the combined load.

Purpose of the study. Identification of rational thermal operating modes of a hybrid solar collector taking into account effective electrical and heating capacity.

Statement of the basic material. Research method – analytical. The photovoltaic battery (PVB) as an energy source can be presented using mathematical model that considers electric power depending on solar radiation flux density [7], environment and module temperature

$$P(t) = P_{nom} k_{l.e} \frac{H}{H_{SC}} [1 + \alpha_p (T_{peb} - T_{SC})],$$

where P_{nom} – rated power of PVB under standard conditions (SC), kW;

$k_{l.e}$ – coefficient of efficiency decrease of PVB,

$k_{l.e}$=0.95; H – solar radiation flux density;

H_{SC} – solar radiation flux density under SC;

T_{SC} – temperature of PVB under SC;

α_P – temperature power coefficient of PVB, K^{-1};

T_{peb} – temperature of PVB.

The following is meant under standard conditions: solar radiation flux density H_{SC}=1 kW/m^2, temperature of PVB surface at STC standard T_{SC}=25 °C.

The quantity of useful heat transferred to a working unit referred to 1 m^2 of the absorber, can be received from the power balance equation which reflects balance between the solar energy falling on PVB, electrical power and heat transfer in surrounding space

$$q_u = H_g R(1 - \eta_{se})(\tau\alpha) - k(T_{peb} - T_a), \text{ W/m}^2,$$

where H_g – radiation flux density on a horizontal platform;

R – conversion factor of radiation flux size from a horizontal platform to an inclined one;

η_{se} – effectiveness ratio of sunlight-to-electricity conversion, taking into account $\eta_{se} = \eta_{se\max}$;

$(\tau\alpha)$ – scaled absorbing capacity of a solar collector;

k – heat loss coefficient;

T_a – ambient temperature.

The useful quantity of heat received from a collector can be found from the following heat equation

$$q_u = c_{ht} g_{ht} (T_0 - T_{in}),$$

where c_{ht} – heat absorption of the heat-carrier;

T_0 – heat-carrier temperature at output of collector;

T_{in} – temperature at input, it can be accepted as constant and equal T_{in}= 15 °C;

g_{ht} – heat-carrier consumption, usually for a solar collector is accepted as g_{ht}=0.015 l/(s·m^2).

The output temperature depends on temperature of an absorber and on heat transfer efficiency from an absorber to heat-carrier. Efficiency of a heat transfer little depends on temperature and it can be accepted equal $\eta_{\text{т}}$ =0.9 [8]. Then the heat-carrier temperature at output will be defined as

$$T_0 = \eta_{\text{т}} T_{peb}.$$

The value of efficiency coefficient $\eta_{se\max}$ depends on temperature. Generally it is power dependence. However in the field of positive temperatures it is close to linear [7]

$$\eta_{se\max} = \eta_{\max SC}[1 + \alpha_p (T_{peb} - T_{SC})],$$

where $\eta_{\max SC}$ – efficiency coefficient of the photovoltaic battery in a point of maximum power at SC;

From a power balance equation we get expression for defining temperature of PVB that operates in a regime of electric power and heat generation

$$T_{peb} = \frac{g_{ht} c_{\text{ht}} T_{in} + kT_a + H_g R(\tau\alpha)\left[1 - \eta_{\max SC}(1 + \alpha_p T_{SC})\right]}{g_{ht} c_{ht} \eta_{\text{т}} + k + H_g R \eta_{\max SC} \alpha_p}.$$

Researches on mathematical model were done with reference to the photovoltaic battery of 1.6 m^2, quantity of cells – 60, electric power in nominal regime – 270 W, open-circuit voltage – 38.4 V, latitude of battery location – 46°. The mathematical model was supplemented with design ratio for definition of intensity of solar radiation and environment temperature according to [9]. Thermal pump work in a variable regime was considered by a separate block of algorithm.

From the data received from the analysis of presented mathematical model follows that the absorber temperature changes essentially both within days and throughout a year. The maximum temperature can reach 70 °C and higher while, according to a condition of economic work of PVB, 50 °C is considered admissible. High temperatures of absorber are characteristic for the summer period – from June till September. Thus the maximum is attained in the middle of day. During the winter period, from October till April, the absorber temperature is insignificant.

High temperature of PVB leads to decrease in productivity. At the same time in summertime, as appears from the received data, despite high temperature of an absorber, the greatest productivity of PVB takes place. This is due to the combined influence of two factors: temperature and intensity of radiation, the last factor is prevailing, especially in summertime when intensity of radiation considerably increases.

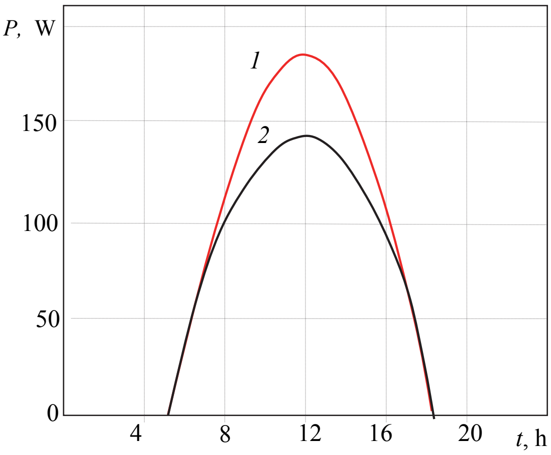

Fig. 1. Change of power of the photovoltaic battery within 24 hours in June at different temperatures of absorber: 1–T_{pvb}=35 °C; 2 – T_{pvb}=var

Fig. 1 shows change of PVB power in June from absorber temperature. Calculation was done for one HSC module with the 1.6 m^2 absorber. One curve represents dependence of PVB productivity at variable temperature of absorber which is formed in passive operating mode of PVB. The second curve is received at active temperature control of absorber in the high point of temperature chart. The absorber temperature here also changed at preheating and cooling, but at the lev-

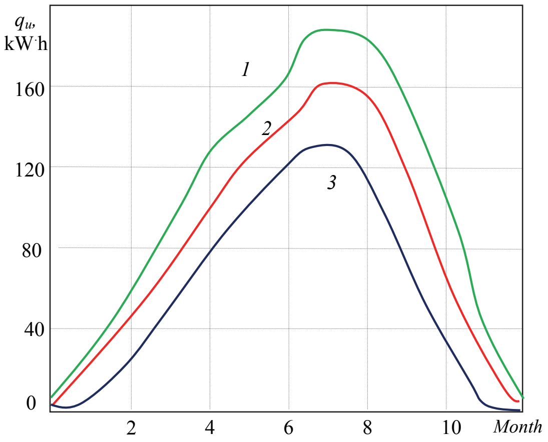

Fig. 2. Dependence of monthly thermal productivity of a hybrid collector on the maximum temperature of absorber: 1 – 20 °C; 2 – 35 °C; 3 – 50 °C

el of 35 °C it was fixed by forced heat removal. Under existing conditions the increase in instant productivity of PVB reaches 22 %. The accepted temperature reporting level is not accidental, such temperature can be attained during the summer period without supercooling the absorber taking into account ambient temperature.

Decrease in temperature of absorber at a forced cooling leads to growth of daily and annual power production. Such growth is manifested during the period from 3rd till 11th month. Change of temperature of absorber allows influencing PVB productivity essentially. Temperature maintenance at 50 °C in summertime results in a gain of daily output of 9 %, at the level of 20 °C to 25 %. During the winter period the PVB operating mode as the thermostatic electric power generator is not actual.

Cooling mode selection is an alternative problem which should consider a number of conditions. One of them is that if the upper heating temperature of absorber is limited to 50 °C, then heat-carrier with such potential can be used for hot water supply. At the same time the satisfaction of heating loading is not possible, while in winter months, keeping in mind the received data, an absorber reheat temperature is essentially below this level.

Cooling temperature selection of absorber in the interval 20…35 °C does not allow to use thermal potential of heat-carrier directly. In this case it is necessary to add the heat transformer (thermal pump) to the system for temperature increase. Thermal pump turning on gives the chance to increase duration of the period of useful heat removal.

Fig. 2 shows dependence of monthly thermal productivity of a hybrid collector on the maximum temperature of an absorber in the conditions of use of the thermal pump for modes with temperature less than 50 °C. The figure proves that decrease in temperature of an absorber from 50 °C to 20…35 °C leads to essential growth of thermal productivity of HSC. This growth is observed practically throughout all year and in winter time heat removal is also possible – taking into account its conversion in the thermal pump. In a monofunctional device (electric generator) mode all heat content, due to lack of heat insulation, is discharged into environment.

According to research, annual manufacture of thermal energy is 50 % higher at restriction of absorber temperature at 20 °C, than upon heating of an absorber to 50ºC. The “35°C” mode increases annual production rate by 22 %. Heating capacity growth is promoted by decrease in thermal losses in these modes: due to low difference of temperatures between an absorber and outdoor air.

Despite high efficiency of the “20 °C” mode, in summertime, when air temperature is high, the most efficient is the “35 °C” mode. At the “35 °C” mode the design temperature at low air temperatures during the winter period, as well as at the “50 °C” mode is not attained, but the removed heat can be converted in the thermal pump.

While using thermal pump the additional energy expenditures connected with its work appear. The feasibility study of low-temperature refrigerating duty of HSC should take into account these expenditures. Fig. 3 shows the data on monthly energy expenditures for the thermal pump drive at tem-

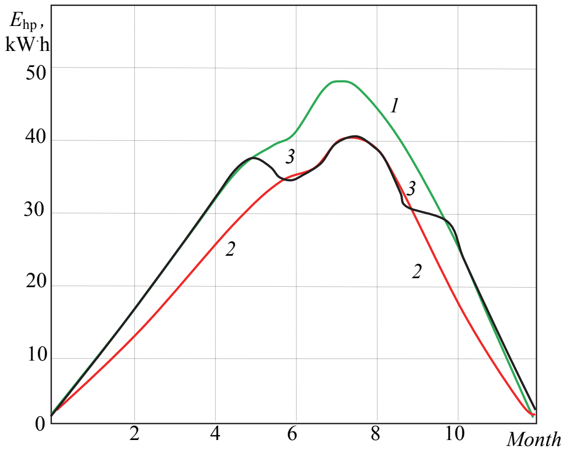

Fig. 3. Monthly energy expenditures for thermal pump drive at temperature increase of heat–carrier up to 50 °C from: 1 – 20 °C; 2 – 35 °C; 3 – 20/35 °C

perature increase of heat-carrier to 50 °C in different modes. The data is received from research of work of compression thermal pump over the temperature increase range from 20 ºC and 35 to 50 °C.

Results. From Fig. 3 it follows that monthly energy expenditures for the thermal pump drive change within a year with a maximum in July. The highest values – for the “20 °C” mode. Type of dependences complies with the data about heat production in HSC. Integration of dependences from Fig. 3 shows the amount of annual energy expenditures for the thermal pump drive: for the “20 °C” mode – 164.73 kW·h/year, for the “35 °C” mode – 133.38 kW·h/year, for the combined “(20/35) °C” mode – 150.2 kW·h/year. Apparently, smaller energy expenditures occur in the “35 °C” mode, but in this mode the heat production is also less. Therefore economic analysis taking into account combined production of heat and electric power is necessary.

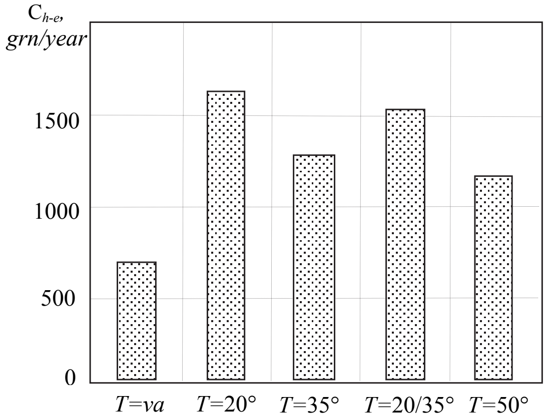

Fig. 4. Total annual cost of heat and electric power generated by HSC, depending on its thermal mode

For such analysis the following alternatives are accepted: basic, with passive temperature conditions – “*T*=var”; with active temperature mode regulation – at the level of 20 °C – “20 °C”; at the level of 35 °C – “35 °C”; at the level of 50 °C – “50 °C”. For calculation the following data was chosen: substitute fuel – gas with combustion heat – 34 MJ/m^3; fuel price – 10000 hrn/(1000 m^3); electricity price – 1.68 hrn/kW·h. Annual cost of the produced energy – electric and thermal (C_{h-e}) depending on the thermal operating mode of HSC, found as the sum of market costs of relevant types of energy minus the cost of electric energy on the thermal pump drive, reflects energy sales revenue. From Fig. 4, where the data on annual cost depending on a system operating mode is presented, it is visible that the “20 °C” alternative possesses the greatest profitability. Slightly lower is the profit in the “(20/35) °C” alternative, which from the technical point of view is the most efficient one. The “50 °C” alternative, in which thermal pump is not used, loses to other designs with heat removal. Energy cost in this heat generation alternative is 19 % lower, than in the “(20/35) °C” mode. The lowest profitability is in the “without absorber cooling” alternative.

Conclusions. Refrigerating duty of HSC offered now (50 °C) does not meet the requirements of effective electric energy generation and year-round heat energy supply to consumers. Generalization of the obtained data allows producing recommendations about organisation of a rational operating mode of a hybrid solar collector. The temperature of absorber of HSC should be at 20…35 °C for stable heat supply. Thus in summertime the temperature level is fixed at 35°C, during other seasons – at 20 °C. For beneficial use of low-temperature potential of a coolant it is necessary to apply thermal pump. The further researches should be aimed at finding effective design of HSC with concentration of an initial power stream.

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