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V. Wysochin, PhD, Assoc. Prof.,
V. Nikulshin, DSc, Prof.,
A. Denysova, DSc, Prof.
Odessa Polytechnic National University, 1 Shevchenko Ave., Odesa, Ukraine, 65044; e-mail: vvwin.od@gmail.com

PECULIARITIES OF THE PV-MD PHOTOMODULE STRUCTURE FORMATION DURING THE ELECTRICAL ENERGY AND DISTILLATE PRODUCTION

В. Височин, В. Нікульшин, А. Денисова. **Особливості формування структури фотомодуля PV-MD при виробництві електричної енергії й дистиляту.** Умови роботи фотомодуля значною мірою визначаються термічним режимом, який впливає на ефективність виробництва електроенергії. Застосування у фотомодулі системи примусового охолодження з реалізацією процесу дистиляції солоних вод дозволяє управляти термічним режимом і одержувати додатковий продукт у вигляді пресної води. Вибір способу керування процесом охолодження й режиму його реалізації дає можливість досягнення раціонального сполучення електричної й технологічної продуктивності фотомодуля. У даній роботі проведені аналітичні дослідження формування температурного поля абсорбера гібридного сонячного колектора (PV-MD) при охолодженні за рахунок випарювання теплоносія і рекуперації теплоти утвореного пару. Метод дослідження дозволяє проаналізувати характеристики PV-MD-колектора - температуру нагрівання абсорбера й охолоджуючої рідини, а також продуктивність системи по дистиляті залежно від структури модуля й умов його роботи. Ціль роботи - розробка методу розрахунку теплотехнічних експлуатаційних характеристик роботи гібридного сонячного колектора в умовах каскадного способу тепломасообміну сольового розчину й дистиляту і виявлення раціональної архітектури пристрою. Використано комплексну математичну модель локального аналізу процесів теплоомасообміну гібридного сонячного колектора для реальних умов сонячної й кліматичної ситуації. Аналіз тепломасообміну у варіантних умовах показав, що ступінь рівномірності температурного поля абсорбера, від якої залежить ефективність виробництва електрики, при застосуванні методу PV-MD така, як для методу PVT. Каскадна рекуперація теплової енергії при методі PV-MD для колекторів типових розмірів за ефективністю обмежується двома ступінями. Отримано узагальнюючі залежності для визначення технологічної продуктивності двоступінчатого PV-MD-колектора по дистиляті й температури абсорбера при зміні зовнішніх умов роботи колектора, які можуть бути використані для оцінки ефективності перетворення сонячної енергії в технологічний продукт.

Ключові слова: гібридний сонячний колектор, метод PV-MD, температурний режим, виробництво дистиляту

V. Wysochin, V. Nikulshin, A. Denysova. **Peculiarities of the PV-MD photomodule structure formation during the electrical energy and distillate production.** The operating conditions of the photomodule are largely determined by the thermal regime, which affects the efficiency of electricity generation. The use of a forced cooling system in the photomodule with the implementation of the salt water distillation process allows you to control the thermal regime and obtain an additional product in the form of fresh water. The choice of the method of controlling the cooling process and the mode of its implementation makes it possible to achieve a rational combination of electrical and technological productivity of the photomodule. In this paper, analytical studies of the formation of the temperature field of the absorber of the hybrid solar collector (PV-MD) during cooling due to the evaporation of the heat carrier and recovery of the heat of the formed steam were carried out. The research method makes it possible to analyze the characteristics of the PV-MD collector, namely, the heating temperature of the absorber and coolant, as well as the performance of the distillate system, depending on the structure of the module and its operating conditions. The aim of the work is to develop a method for calculating the thermal performance characteristics of the hybrid solar collector in the conditions of a cascade method of heat and mass transfer of salt solution and distillate and to identify the rational architecture of the device. A complex mathematical model of local analysis of heat and mass exchange processes of a hybrid solar collector for real solar and climatic conditions is used. The analysis of heat and mass transfer in variant conditions showed that the degree of uniformity of the absorber temperature field, which depends on the efficiency of electricity production, when applying the PV-MD method is the same as for the PVT method. Cascade recovery of thermal energy using the PV-MD method for collectors of typical sizes is limited in efficiency to two stages. The generalized dependences for determining the technological productivity of the two-stage PV-MD collector in terms of distillate and absorber temperature when the external operating conditions of the collector change, which can be used to evaluate the efficiency of converting solar energy into a technological product, have been obtained.

Keywords: hybrid solar collector, method PV-MD, temperature regime, distillate production

Introduction

The temperature of the photomodule significantly affects the efficiency of electric energy production [1, 2]. Various methods of cooling are used to reduce the heating temperature of the module. Active methods are increasingly being chosen for modern photo modules. Such methods allow the utilization of cooling heat, which increases the overall energy efficiency of the device [1 – 4]. In a PVT

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solar collector, photovoltaic elements are cooled using an active heat removal system with a liquid coolant through channels in the back of the module [1 – 4]. In the PV-MD type hybrid collector, it is possible to remove heat from the absorber of the photogenerator and use it for water evaporation in one device. If an aqueous solution of salts is used as such a carrier, the result of the process will be distilled water [5, 6]. Features of this technology affect important issues related to the reduction of land resources alienated for the placement of power plants and the production of drinking water. Solar distillation, primarily of seawater, is of great interest. However, low efficiency restrains its spread. The emergence of the MSMD method – multistage membrane distillation, which is part of the PV-MD installation, improves the efficiency of water distillation due to the regeneration of the latent heat of con-condensation of steam for heating water on the connected stages of the device [5, 6]. The three-stage energy recovery and distillation proposed in [5] for the PV-MD module allows for the achievement of the efficiency of the device, which significantly exceeds the indicators of conventional solar stills. At the same time, the PV panel generates electricity with the energy efficiency of a conventional commercial module. The introduction of a heat exchange device into a photocell forms characteristic temperature fields in individual elements of the module. Since the temperature regime of the PV-MD collector determines its performance in terms of distilled water and electricity, for a full assessment of the wide application of the method, a justification of the thermal regime of the device is necessary.

Analysis of recent research and publications

Three-stage energy recovery in the MSMD device is considered promising [5]. Each stage consists of four separate layers: a thermally conductive layer, a hydrophilic porous vaporization layer, a hydrophobic porous MD membrane layer for vapor penetration, and a water vapor condensation layer.

At each stage of the MSMD device, heat is transferred through the thermally conductive layer to the underlying hydrophilic porous layer. The incoming water in the hydrophilic porous layer is heated to the formation of water vapor. Water vapor passes through the hydrophobic layer of the porous partition and condenses in the condensation layer in the form of pure water. The driving force for steam vaporization and condensation is the vapor pressure difference caused by the temperature gradient between the vaporization and condensation layers. At each stage, the latent heat of water vapor released during the condensation process is used as a heat source for vaporization at the next stage. The multistage design assumes the reuse of vaporization heat, increasing the productivity of the distillation process relative to a single cycle [5].

Experimental studies of the model of the three-stage device in [5] showed that the temperature of the heat-conducting layers with standard irradiation of the AM1 absorber and its absorption capacity of 0.87 is (61.8; 55.1; 47.5 and 38.4) °C, in the direction from the top to the bottom layer. Such data testify to the significant potential of the heat and mass transfer process.

Studies have shown that the distillate productivity at three stages is 1.65 $\mathrm{kg \cdot m^{-2}\ h^{-1}}$. In [5] it was noted that the dependence between distillate productivity and solar radiation intensity is linear and the efficiency of electricity generation by a solar battery is stable within 11.1...11.6 % at different irradiation intensities. The presented data were obtained on models with an absorber size of 11...16 $\mathrm{cm^2}$. The modeling factor was not discussed in [5], therefore, for widespread use on devices of generally accepted sizes, additional research is needed.

Analytical models are usually used when studying the thermal modes of operation of collectors [7]. Such models differ in the method and detail of the mathematical description of the operation of objects that take place in significantly changing conditions. Obtaining the necessary information directly depends on the completeness and adequacy of the description. An important factor in the research of various models is the generalization of the obtained results in the format necessary for engineering implementation, which is not done in most cases.

Purpose

Development of a method for analyzing the operational heat-technical characteristics of the PV-MD hybrid solar collector for real operating conditions determined by dimensions and external influences, identifying the rational architecture of the device and presenting experimental data in the form of generalized models.

Presentation of the main material

The model structure of the two-stage device is shown in Fig. 1. The solution enters the hydrophilic porous layer of the second stage, is heated through a separating wall from the distillate condensate, and after evaporation passes to the first stage, in which it also undergoes the stages of heating when interacting with the absorber and evaporation in the hydrophobic layer of the porous partition.

The external conditions of heat transfer in the collector are the intensity of radiation of the absorber and heat exchange with the environment. The internal conditions are formed during the heat exchange between the absorber and the salt solution, during the evaporation of water and the condensation of steam in the condenser, as well as between the condensate and the solution through the separating heat-conducting wall. These processes are described by the following system of energy conservation equations.

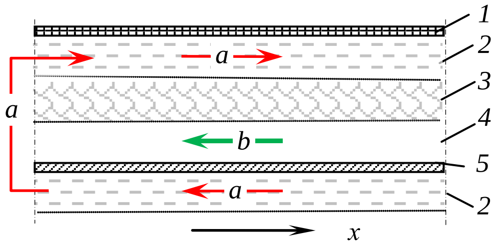

Fig. 1. Calculation and technological scheme of the collector: *1* – absorber; *2* – hydrophilic porous layer; *3* – hydrophobic layer of the porous partition; *4* – condenser; *5* – heat-conducting wall. Arrows show the direction of movement of solution (*a*) and distillate (*b*) flows

For the absorber:

$$H(\tau\alpha)(1-\eta_{ph})-h_{abs-a}(t_{abs}-t_a)-h_{abs-s}(t_{abs}-t'_s)=0,$$

where H – intensity of solar radiation;

$\tau\alpha$ – optical characteristics of the collector;

η_{ph} – Efficiency of conversion of solar energy by the collector;

h – heat transfer coefficient;

t – temperature.

For the solution in the first step:

$$h_{abs-s}(t_{ph}-t'_s)-(cg)_s\frac{dt'_s}{dx}-g'_d r=0,$$

where c – heat capacity;

g – flow rate витрата;

r – heat of vaporization.

For distillate in the condenser of the first stage:

$$U_{d-s}(t'_d-t''_s)-(cg)_d\frac{dt'_d}{dx}-g'_d r=0,$$

where U – heat transfer coefficient.

For the heater and evaporation of the solution in the second stage:

$$U_{d-s}(t'_d-t''_s)-(cg)_s\frac{dt''_s}{dx}-g''_d r=0.$$

Here the accepted indices are: *abs* – absorber; *s* – solution; *d* – distillate.

The value of the efficiency of the photocell η_{hp} depends on the temperature, and in the region of positive temperatures can be represented by the dependence [7]:

$$\eta_{hp}=\eta_{\max\mathrm{SC}}[1+\alpha_P(t_{abs}-t_{\mathrm{SC}})],$$

where $\eta_{\max\mathrm{SC}}$ – photocell efficiency at the point of maximum power under standard conditions (SC);

t_{SC} – the photocell temperature at SC; α_P coefficient of the power of the photocell.

The system of equations is supplemented with boundary conditions characteristic for the operation of solar devices [7]. The boundary conditions are specified by the dependence obtained during data processing [5] from the determination of distillate productivity when implementing the MSMD method, kg/(m^{2}h):

$$g_d=0.0223\cdot t_{abs}-0.3181.$$

The input flow rate of the solution is taken to be equal to 4.2 kg/(m^{2}h) [5]. The characteristic size of the module was determined by its length, which was taken according to typical values – 1.8...2.0 m. Boundary conditions were selected for the area with a latitude of 46° for different seasons.

The solution to the system of equations was the local temperatures of the absorber, solution, and distillate, as well as the distillate flow rate. The system of equations was solved by a numerical method. Since the temperature change in the system occurs along the flow of coolants, the normalization of the considered indicators with respect to the width of the module is introduced.

The nature of the temperature change of the solution along the flow in the first and second stages, of the distillate in the first stage is shown in Fig. 2.

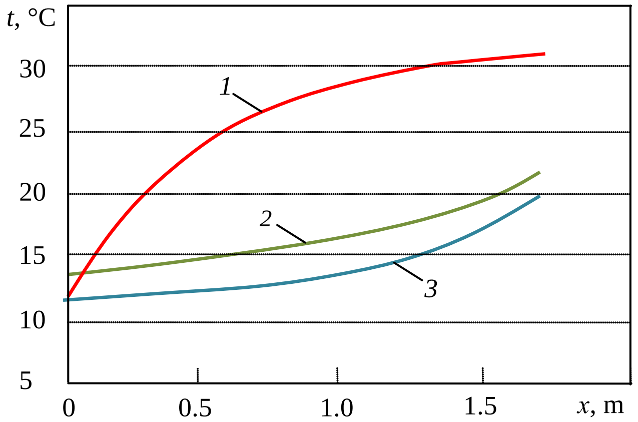

Fig. 2. The nature of the temperature change of the solution along the flow in the first (*1*) and second stages (*2*), as well as of the distillate in the first stage (*3*)

The temperature of the solution in the first stage, despite the loss of heat during water evaporation, increases along the flow. Accordingly, the temperature of the absorber also increases. However, the intensity of such growth subsequently decreases, asymptotically approaching the temperature to the limit value already noticeable under these conditions. This nature of the dependencies is explained by the process of reshaping the heat balance in the initial part of the flow – at a low temperature of the solution coming out of the second stage, and a significant influx of heat with radiation. As the solution warms up, the amount of heat produced in the absorber is increasingly spent on distillation, the intensity of which depends on the temperature level. The amount of evaporated water increases along the stream (Fig. 3). The last type of dependence is also characterized by a decrease in the growth of the function along the stream and the formation of an asymptotic approximation to a certain value. The largest amount of evaporated water depends on external influencing factors. Despite the presence of an asymptotic approach to such a value, apparently, there is no need to limit the length of the channel (module) by this factor.

In the second stage, the temperature of the solution changes less. Its formation is influenced by the thermal potential of the first-stage distillate, as a profitable item, and the extraction of heat for evaporation. The thermal potential of the distillate is insufficient for significant heating of the solution, and the temperature of the solution under distillation conditions even decreases along the flow. Thus, the second stage does not perform the role of a heater of the solution, as expected when choosing a method of intensification of distillation in the first stage. However, lowering the temperature of the solution entering the device is a positive factor, because it contributes to a deeper cooling of the absorber.

It should be noted that the direction of the solution flows in the stages is opposite, and at the initial value of the coordinate x, the flow transitions from the second stage to the first, which is marked by the equality of temperatures in Fig. 2.

The distillation process in the second stage, due to the low potential of the solution, is characterized by a low intensity (Fig. 3), and in the region of stabilization of the temperature of the solution flow, which takes place at the end of the channel of the stage, the manifestation of this process becomes insignificant. The low intensity of heat and mass exchange processes at this stage is emphasized by the absence of practically perceptible influence of external conditions. In general, in the second stage,

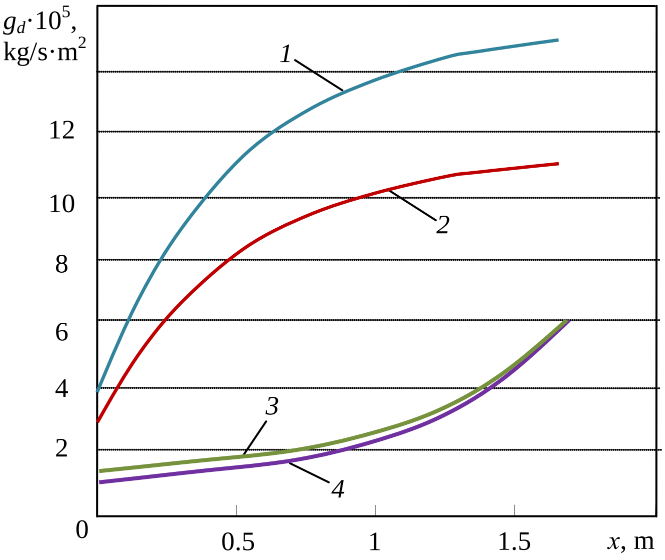

Fig. 3. Change in the local intensity of distillation along the module in the first and second stages: *1* – summer/1st stage; *2* – winter/1 stage; *3* – summer/2nd stage; *4* – winter/2 stage

the formation of the flow potential necessary for the distillation process in the next, lower, stage does not occur.

The obtained data, which determine the productivity of the distillate in the first stage depending on the external conditions of operation, are summarized in the form, kg/(s.m):

$$g'_d = 0.0123 - 1.8 \cdot 10^{-5} H - 3.1 \cdot 10^{-3} / t_a .$$

The functional dependence for determining the average temperature of the absorber, which summarizes the influence of the determining parameters, is obtained in the form:

$$\overline{t}_{abs} = 32.2 + 0.177 \cdot t_a - 0.00783 \cdot H .$$

Since the optimization of the operating modes of heat engineering devices assumes the task of a basic level of comparison, in this method, the initial temperature of the salt solution, the value of which was chosen to be equal to 20 °C when obtaining the formulas, is taken as such a basis. The choice is due to the possibility of controlling this parameter in real conditions. It is important to compare the main known ways of forming the temperature of the absorber. The temperature of the absorber during distillation is significantly lower compared to natural cooling (Fig. 4). Moreover, this regime is characterized by significant resistance to the influence of external factors, such as the temperature of the outside air and the intensity of insolation. Comparison of data for PVT systems, where liquid cooling is used without distillation [7], and PVMT shows that the temperature levels of the absorbers are close. For example, for summer operating conditions, the average temperature of the absorber in the first case is 35 °C, and in the second – 34 °C. When comparing, the hydraulic modes of operation of the modules are shown to be typical for these systems; for the PVT module, the mode corresponds to the data [7], found to be rational. It should be noted that the estimated consumption of coolant in the first case is an order of magnitude greater than in the second.

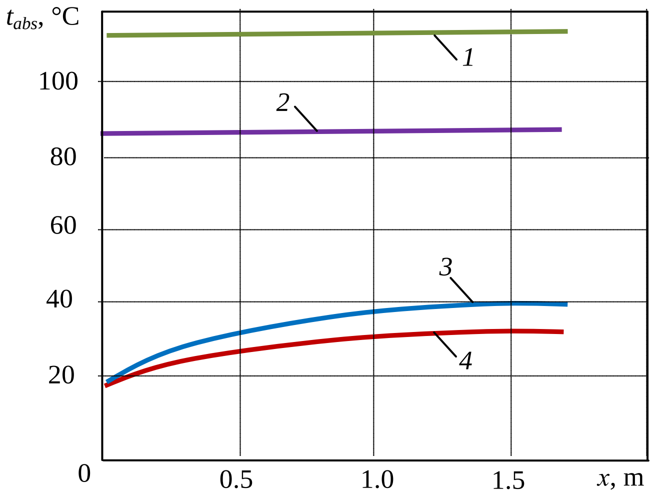

Fig. 4. Temperature change of the absorber along the module in modes: without cooling (*1* – summer; *2* – winter); cooling with distillation (*3* – summer, *4* – winter)

Thus, the efficiency of forming the temperature regime for the PVMT system, i.e. the conditions for generating electricity, is quite high and is on the same level as other cooling systems.

Conclusions

Analytical studies of the influence of operational heat-technical characteristics of the PV-MD hybrid solar collector in the conditions of the cascade method of heat-mass exchange of salt solution and distillate were carried out in order to identify the rational architecture of the device.

According to the results of the study, it is shown:

In the second stage, the thermal potential of the distillate is insufficient to significantly heat the solution, and the temperature of the solution under distillation conditions decreases along the flow, which indicates the low efficiency of the stage as a solution heater.

A decrease in the temperature of the solution entering the device in the second stage is a positive factor, because it contributes to deeper cooling of the absorber in the first stage.

Cascade recovery of thermal energy in the PV-MD method for collectors of typical sizes should be limited to two stages in terms of efficiency.

Generalized dependences for determining the distillate collector productivity and the average temperature of the collector absorber on external operating conditions were obtained. The proposed generalizations of the model can be used to evaluate the efficiency of the conversion of solar energy into electricity of the combined solar device in mode optimization tasks.

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Височин Віктор Васильович; Victor Wysochin, ORCID: http://orcid.org/0000-0003-2279-203X
Нікульшин Володимир Русланович; Vladimir Nikulshin, ORCID: http://orcid.org/0000-0001-5946-8562
Денисова Алла Євсіївна; Alla Denysova, ORCID: http://orcid.org/0000-0002-3906-3960

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