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Biaxial Heat Balance Model of a Solar Collector

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In research, solar collectors and photovoltaic systems (PV/T) are considered, which are one of the most promising systems of renewable energy sources. Electricity, which is produced by photovoltaic panels, has great potential, but there may be technological shortcomings, which do not give maximum efficiency. The main goal of our research is to develop a universal model of heat exchange processes for optimizing the design features of PV/T systems at the stages of design and variability, which allows us to increase the term of service of such systems and their efficiency. The expanded model allows you to change more practical parameters for two coordinates of a flat collector, such as to change the consumption of thermal energy, thermal support of the absorber plate, heat exchange, operating temperature, etc. The results of model investigations correlate with the experimental data. On the basis of the proposed model, a software product for the modeling of PV/T systems was developed and tested on the experimental results of those ready-to-wear PV/T systems. In the course of carrying out the expansions, depending on the basic parameters, the heating was removed when one segment of the collector was passed by approximately 1.5 °C. The designated increase in temperature was reached at a heat transfer rate of 0.6 m/s, which allows high rates to be achieved. The most optimal will be the heating when passing through the collector by 5 °C, which will allow to reduce the heat transfer rate to 0.2 m/s and significantly reduce the amount of electricity consumed by the pump. The variation of the expanded model allows to implement a wide range of optimization tasks at the stages of designing and optimizing solar collectors and PV/T systems, to take the optimal design parameters to achieve the greatest efficiency and minimum occupancy.

Keywords: Solar collector, PV/T system, Math model, Optimization, Efficiency.

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1. INTRODUCTION

Combined photovoltaic systems (PV/T), allowing the generation of electrical and thermal energy, continue to gain relevance. Such systems look attractive in terms of increased overall efficiency and reduced area required for their placement. The efficiency of the most advanced solar cells does not exceed 35 %, while the efficiency of PV/T systems can reach 70 % [1].

However, the development of such systems relies exclusively on experimental studies, and the optimization of their design is carried out exclusively in practice. This leads to the impossibility of the rapid development of this direction as a whole and is reduced to solving particular problems.

We previously proposed a basic uniaxial model of the heat balance of such a system [2], which takes into account all significant parameters of the system. Such a model allows solving optimization problems related to thermal processes in the systems under consideration, and its study has shown its efficiency. However, taking into account the flowing coolant and more complex processes in real systems requires an extension of the model in consideration of processes along two axes.

Therefore, the purpose of this article was to create a biaxial model of the heat balance of a PV/T system for solving optimization problems of such systems in relation to real systems used in practice. The development of a universal model will cover a wide range of tasks and simplify optimization to improve the efficiency of modern PV/T systems.

2. HEAT BALANCE MODEL

The temperature distribution in the direction of fluid flow along the OY axis is a factor in taking into account the overall heat transfer of the fluid. The temperature gradient created in the direction of the fluid flow increases the heat loss from the collector and leads to an increase in the heating of the fluid in one pass through a pipe of a given cross section and length (given system geometry). Taking into account the heat and mass transfer in the tube for the flowing liquid, the difference between the temperature of the liquid at the outlet and at the inlet to the collector is determined by an expression that depends on a variety of system parameters.

The expression for the amount of heat that is transferred from the liquid absorber plate inside the tube was obtained in the previous research [3]:

$$q_u' = WF'(I - U_L(T_f - T_a)), \tag{1}$$

where F' is the collector efficiency from equation [3]:

$$F' = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L(W-D)F+D}+R_p\right]},$$

$$\frac{1}{U_0} = W\left[\frac{1}{U_L(W-D)F+D} + R_p\right]. \tag{2}$$

Ultimately, useful thermal energy from the collector must be transferred to the fluid in the pipe. The resistance to heat flow in the fluid is the result of the interaction and resistance of the tube surface to the fluid. The collector efficiency depends on the inner diameter of the pipe, the heat transfer coefficient between the liquid and the walls of the tube, the conductivity of the material, which in turn depends on the thermal conductivity and the geometry of the system, i.e., the average thickness and width per unit length.

Physical interpretation of F' is the result of the analysis of equation (1). At a specific point, F' is the ratio of the useful energy gain to the useful gain that would be obtained if the absorption surface of the collector was at a steady-state liquid temperature [3, 4]. For a given and most (but not all) geometries, the interpretation of the parameter F' becomes clear when it gets on that the denominator of equation (2) is the resistance to heat transfer from the fluid to the surrounding air. This resistance is symbolized $\frac{1}{U_0}$. The numerator indicates the resistance to heat transfer from the absorber plate to the ambient air $\frac{1}{U_L}$. Thus, F' is the ratio of these two heat transfer coefficients or the efficiency of the collector fin:

$$F' = \frac{U_0}{U_L}. \tag{3}$$

The efficiency of the collector is nearly constant for any collector design and fluid flow. U_L to H, k_w to B, U_L to h_w ratios and the parameter of rib efficiency F are the only variables in equation (2) that can be functions of temperature. For most collector designs, F is the most important of these variables in determining F'. Factor F' is a function of U_L and h_w, each of which has some slight temperature dependence, but has a significant impact when the liquid flows along the tube, that is, the direction of the OY axis we have chosen.

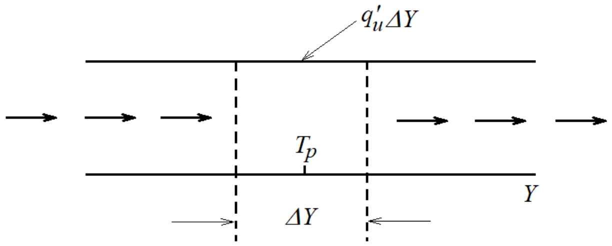

Fig. 1 – Energy balance of liquid along the OY axis

The conductivity of a material can be very important in accurately describing the characteristics of a reservoir. Whillier and Saluja [5] experimentally showed that simply routing or fixing tubes to a sheet result in low joint conductivity and a significant loss in performance and efficiency. They concluded that it is necessary to have good metal-to-metal contact in order for the conductivity of the bond to be higher than 30 $\frac{W}{m \cdot K}$. It is expected that the efficiency of the collector decreases with increasing tube center distance and increases with both material thickness and thermal conductivity. Increasing the total loss factor reduces F'.

Useful thermal energy per unit length, calculated according to equation (1), is ultimately transferred to the liquid. The fluid enters the collector at temperature T_{fi} (inlet) and rises until T_{fo} (outlet). Referring to Fig. 1, we can express the energy balance of a fluid flowing through a single tube of length Y as

$$\left(\frac{\dot{m}}{n}\right)C_p T_f\Big|_y - \left(\frac{\dot{m}}{n}\right)C_p T_f\Big|_{y+\Delta y} + \Delta y q'_u = 0, \tag{4}$$

where $\dot{m}$ is the mass flow rate of the coolant in the collector, n is the number of parallel tubes in the collector [2]. Dividing by y, finding the limit when y tends to zero, and substituting equation (1) instead of q'_u, we get

$$\dot{m}C_p \frac{dT_f}{dy} - nWF'\left[I - U_L(T_f - T_a)\right] = 0. \tag{5}$$

Assuming that F' and U_L do not depend on the position [6, 7], the solution for the liquid temperature in any position y (assuming that the liquid temperature at the inlet is equal to T_{fi}) will be

$$\frac{T_f - T_a - \frac{I}{U_L}}{T_{fi} - T_a - \frac{I}{U_L}} = \exp\left(-\frac{U_L nWF' y}{\dot{m}C_p}\right). \tag{6}$$

If the collector has length L in the direction of flow, the temperature of the liquid at the outlet T_{fo} is found by replacing L by y in equation (6) Value $nWF' = S$ is the total area of the collector [2]:

$$\frac{T_{fo} - T_a - \frac{I}{U_L}}{T_{fi} - T_a - \frac{I}{U_L}} = \exp\left(-\frac{U_L S F'}{\dot{m}C_p}\right). \tag{7}$$

For convenience, let us define a value that relates the actual efficiency of the energy (heat) of the collector with the efficiency if the entire surface of the collector was at the temperature of the liquid at the inlet. This value is called the heat removal coefficient of the collector F_R. In the form of an equation, it is expressed [2]:

$$F_R = \frac{\dot{m}C_p(T_{fo} - T_{fi})}{S(I - U_L(T_{fi} - T_a))}. \tag{8}$$

The coefficient of heat removal from the collector can be expressed as

$$F_R = \frac{\dot{m}C_p}{SU_L}\left[\frac{(T_{fo} - T_{fi})}{\frac{I}{U_L} - (T_{fi} - T_a)}\right] = \frac{\dot{m}C_p}{SU_L}\left[\frac{\left[\frac{I}{U_L} - (T_{fi} - T_a)\right] - \left[\frac{I}{U_L} - (T_{fo} - T_a)\right]}{\frac{I}{U_L} - (T_{fi} - T_a)}\right], \tag{9}$$

or

$$F_R = \frac{\dot{m}C_p}{SU_L}\left[1 - \frac{\frac{I}{U_L} - (T_{fo} - T_a)}{\frac{I}{U_L} - (T_{fi} - T_a)}\right], \tag{10}$$

which from equation (7) can be expressed as

$$F_R = \frac{\dot{m}C_p}{SU_L}\left[1 - \exp\left(-\frac{SU_L F'}{\dot{m}C_p}\right)\right]. \tag{11}$$

It is convenient to enter and determine the collector flow coefficient F'' as ratio F_R to F' and write as

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_p}{SU_L F'}\left[1 - \exp\left(-\frac{SU_L F'}{\dot{m}C_p}\right)\right]. \tag{12}$$

This reservoir capacity factor [8] is a function of a single variable, the dimensionless reservoir capacitance $\frac{\dot{m}C_p}{SU_L F'}$, and shown in Fig. 2.

Value F_R is equivalent to the efficiency of a conventional heat exchanger, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. The maximum possible increase in useful energy (heat transfer) in a solar collector occurs when the entire collector is at the temperature of the liquid at the inlet; heat loss to the environment is minimal [9, 10]. The coefficient of heat removal from the collector, multiplied by this maximum possible increase in useful energy, is equal to the actual value of useful energy q'_u, normalized per unit area:

$$q'_u = F_R\left[I - U_L(T_{fi} - T_a)\right]. \quad (13)$$

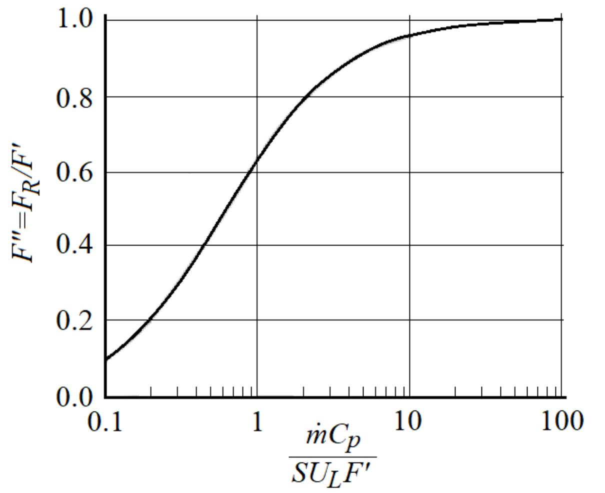

Fig. 2 – Reservoir capacity factor as a function of $\frac{\dot{m}C_p}{SU_LF'}$

This is an extremely useful equation (12) applicable to almost all flat plate collectors. It calculates the gain in usable energy as a function of inlet fluid temperature. This is a convenient representation when analyzing PV/T systems because the inlet fluid temperature is usually known. However, the losses depending on the temperature of the liquid at the inlet are too small, since the losses occur along the entire length of the collector plate, and the plate has a constantly increasing temperature in the direction of flow. Influence of the coefficient F_R is to take into account the change in the value of useful energy from what it would be if the entire absorber plate of the collector was at the temperature of the liquid at the inlet, to what actually happens. As the mass flow through the collector increases, the temperature rise through the collector decreases.

This results in lower losses as the average collector temperature is lower and the usable energy increases accordingly. This increase is reflected by an increase in the heat sink coefficient of the collector F_R as the mass flow increases. It is logical that F_R can never exceed collector efficiency F'. When the flow rate becomes very high [2, 11], the temperature rise from the inlet to the outlet decreases to zero, but the temperature of the absorbing surface will still be higher than the temperature of the liquid. This temperature difference is explained by the efficiency factor. The resulting ratio is a convenient way to express the flow rate when the collector area is a design variable, since increasing both ratios will keep the value almost constant F_R.

To evaluate the performance of a collector, it is necessary to know the total loss factor and the heat transfer coefficients of the fluid. However, U_L, and h_w are somewhat dependent on temperature. The average temperature of the liquid can be found by integrating equation (8) from zero to L:

$$< T_f >= \frac{1}{L}\int_o^L T_f(y)dy. \quad (14)$$

3. APPROBATION OF THE MODEL

Based on the proposed model, software was developed for carrying out calculations, taking into account all system parameters. The appearance of the main program window is shown in Fig. 3.

An analysis of the obtained results confirms full compliance with the results obtained for the particular case of a uniaxial model [3] and the reference results obtained in experimental studies [11-15].

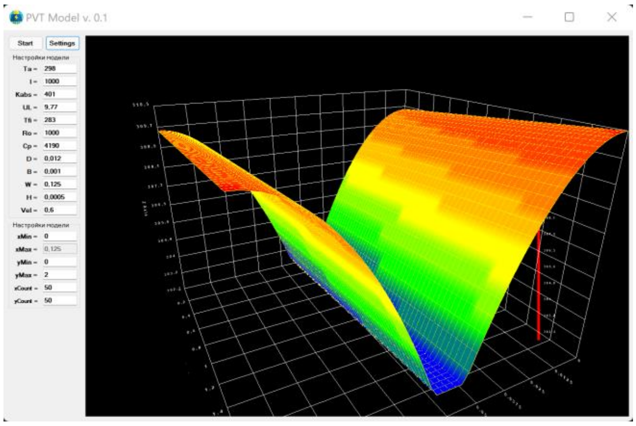

Fig. 3 – Main window view of the developed program PV/T model

When carrying out calculations using the parameters indicated in Fig. 3, heating of the coolant was obtained when passing through one segment of the collector for approximately 1.5 °C. The indicated temperature increase was achieved at a sufficiently high coolant rate of 0.6 m/s. The most optimal will be to achieve heating of the coolant when passing through the collector to 5 °C [16-18], which will reduce the flow rate of the coolant down to 0.2 m/s and significantly reduce the cost of electrical energy for the operation of the pump.

Using the model to optimize geometric parameters will also allow achieving a more uniform temperature distribution over the surface for using the collector together with solar cells as part of a PV/T system.

4. CONCLUSIONS

Further development of the model of heat exchange processes in plates of the heat collector absorber made it possible to establish a full-fledged two-axis model of the heat collector processes for operation as part of a PV/T system. The model allows taking into account all significant parameters of the system.

Based on the proposed model, a program was created for express modeling of the parameters of the system being developed. Basic calculations were carried out, which confirmed the efficiency of the model, its compliance with a uniaxial model investigated earlier, as well as reference experimental data.

Using the advanced model will allow solving a wide range of optimization problems at the stages of designing and optimizing solar collectors and PV/T systems, obtaining optimal design parameters to achieve the highest efficiency and the lowest cost.

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Двовісна модель теплового балансу сонячного колектора

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В роботі розглядаються сонячні колектори та термофотоелектричні системи (PV/T), що є одними з найперспективніших систем відновлюваних джерел енергії. Електроенергія, що виробляється фотоелектричними панелями, має великий потенціал, але й має технологічні недоліки, що не дають отримати максимальну ефективність. Метою нашого дослідження є розробка універсальної моделі теплообмінних процесів для оптимізації конструктивних особливостей PV/T систем на етапах проектування та виробництва, що дозволить збільшити термін служби таких систем та їх ефективність. Розроблена модель дозволяє враховувати більшість практичних параметрів за двома координатами плаского колектора, які враховують втрати теплової енергії, тепловий опір пластини абсорбера, теплообмін, робочі температури, тощо. Результати проведених модельних розрахунків корелюють з експериментальним даними. На основі запропонованої моделі розроблено програмний продукт для моделювання PV/T систем та проведено його тестування на відомих експериментальних результатах та готових PV/T системах. При проведенні розрахунків з використанням базових параметрів отримано нагрівання теплоносія при проходженні одного сегмента колектора приблизно на 1,5 °C. Зазначене зростання температури досягається при швидкості теплоносія 0,6 м/с, що є досить великою швидкістю. Найбільш оптимальним буде досягнення нагрівання теплоносія при проходженні через колектор на 5 °C, що дозволить знизити швидкість протікання теплоносія аж до 0,2 м/с і значно знизити витрати електричної енергії на роботу помпи. Використання розробленої моделі дозволить вирішувати широке коло оптимізаційних завдань на етапах проектування та оптимізації сонячних колекторів та PV/T систем, отримувати оптимальні параметри конструкції для досягнення найбільшої ефективності та мінімальної собівартості.

Ключові слова: Сонячний колектор, PV/T система, Математична модель, Оптимізація, Ефективність.