Hydraulic and Thermal Engineering Calculation in the Laminar Mode of Operation of a Photoelectric Thermal Battery

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Abstract: Efficient conversion of solar energy into electrical and thermal energy has become a major goal of researchers around the world. In this regard, the authors have developed photovoltaic thermal installations to efficiently convert solar energy into electricity and heat. This article briefly analyses the development of a photovoltaic thermal system for efficient cooling of the photovoltaic part with various methods and coolants. A photovoltaic thermal battery (PTB) with a cooling system based on multichannel polycarbonate has been developed. The dimensions of the cellular polycarbonate channels are 7 x 12 mm^2. Water flows horizontally through more than 200 channels in parallel streams. The thickness of the cellular polycarbonate sheet is 4 mm. The PTB cooling system is a structure consisting of a sheet of cellular polycarbonate and channel openings, which are attached to two perpendicularly located polypropylene tubes using transparent silicone sealant. This design of the cooling system (absorber) has less weight and a lower cost compared to traditional metal structures, and the cellular polycarbonate sheet in the PTB is protected from direct exposure to ultraviolet radiation emitted by the sun. The model of a combined PTB installation based on a "photovoltaic battery and heat converter" (PVB-TC) was implemented using COMSOL Multiphysics 5.6. Hydraulic and thermal calculations were carried out in laminar mode, and PTB parameters were determined: water temperature at the outlet of the absorber PTB t_2, water pressure at the inlet of the absorber t_1, and water flow G at the corresponding water velocities W=0.1 m/s, 0.2 m/s, and 0.3 m/s, taking into account three values of ambient temperature - 25 °C, 35 °C, and 45 °C. The modelling process took into account the use of concentrated solar radiation in a combined PEP-TEP installation using weakly concentrating reflectors.

1 INTRODUCTION

The sun, by human standards, is an inexhaustible source of energy. There are devices that convert solar energy into electrical energy. Direct conversion of solar radiation into electrical energy is carried out by photoelectric modules (PEM). An increase in the PEM temperature leads to a decrease in its efficiency.

Therefore, it is necessary to cool the PEM. PEM cooling methods are divided into passive and active, where the coefficient of performance (COP) of polycrystalline silicon PEM depends inversely on the temperature of solar cells (SC) [1-3]. The paper [4] provides an overview of various methods of PEM cooling. However, in most of these cooling methods, the heat generated in the PEM is removed to the environment. Water and air are mainly used as a heat carrier [5-11]. The method of active cooling with water is used in a photo-thermal converter (PTC), which provides consumers with electricity and hot water (thermal energy). Solar cells are usually attached to an absorber plate to improve thermal contact [12–16]. However, Avezov et al. [17] concluded that water-based PTC systems are more efficient than air PTC systems.

Egyptian researchers analyzed all methods of cooling solar modules. Their review includes passive and active cooling methods, cooling with phase change materials (PCM), and cooling of PCM and other additives such as nanoparticles or porous metal [18-21].

The works [22-28] present experimental research of PTC for generating electricity and hot water. The paper [29] considers the electrical and thermal power of solar hot water systems with single plate collectors to study the mechanisms for determining the output parameters.

The use of polymer and plastic materials in photovoltaic thermal systems has been studied in [30, 31]. Experimental and analytical studies were carried out to study the thermal and energy parameters of PV-T using plastic and polymer materials in plant designs. In [32], the authors conducted a comparative study by modelling PV-T systems of different technologies using the Matlab simulation and ANSYS Software software packages. A reliability study has been conducted on PV-T based on thin-film solar cells based on different technologies (binary, ternary, and quaternary materials). The efficiency obtained by cadmium telluride (CdTe), copper indium diselenide (CIS), and copper indium gallium diselenide (CIGS) PV-T collectors has been found to be more important than the efficiency obtained by silicon and amorphous silicon-based PVT collectors (a-Si), ranging from 47% to 57%. In addition, with this type of PV-T, the outlet temperature of the coolant temperature reaches a value of 43.2°C, which is higher than the value obtained by PV-T collectors based on silicon and amorphous silicon.

In [33], the authors developed an energy model and computer simulation of PV/T for application in buildings. The results show that the overall electrical and thermal efficiencies are 9.39% and 37.5%, respectively.

In this paper, we propose a mathematical model of an installation consisting of a photovoltaic module and an absorber (heat converter) made of a polymer material. The mathematical model of the PEC-THC installation was implemented using the COMSOL Multiphysics 5.6 program.

When cooling the PEC from the back side with water, the surface temperature of the PEC, the amount and final temperature of the cooling water, which, at a sufficient temperature, could be used in the hot water supply system, are of interest.

For the research, a model of a photoelectric thermal battery was chosen, shown in Figure 1, in which a polycarbonate film with channels of a square section 8x8 мм^2 in size was chosen as a cooling element. Cooling water flows through the channels.

2 MATERIALS AND METHODS

For the calculation in COMSOL Multiphysics 5.6, the geometric dimensions of the model and the structure of the PEC materials were specified.

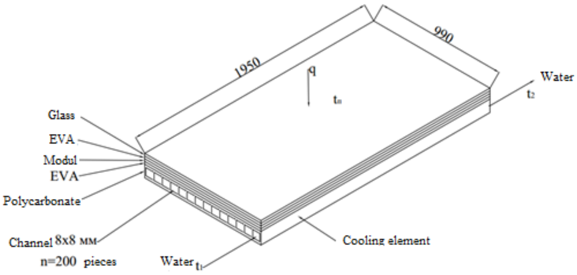

Figure 1: Model for the research of photovoltaic thermal battery.

In addition, the following were asked:

1) Flux density of supplying solar radiation: q, W/m^2.
2) Mode of water flow: Re < 2300.
3) Water inlet temperature: t_1, °C.
4) Ambient air speed: V, m/s.
5) Barometric pressure: P, bar.
6) Three speeds of water in the channel: W, m/s (0,1,0,2 and 0,3 m/s).

As a result of the calculation under the given conditions, we obtained:

1) Average surface temperature of PEC.
2) Outlet water temperature: t_2, °C.
3) Inlet pressure of water: P_{vx}, Pa.
4) Water flow through the channel: G, g/s.

3 RESULTS AND DISCUSSIONS

The results of the COMSOL Multiphysics 5.6 calculation are shown in Table 1. The average temperature of the PEC surface is ~45°C (Figure 2). Table 1 shows the results of calculations of the outlet water temperature t_2, the inlet water pressure and the water flow rate G at water velocities W=0.1, 0.2 and 0.3 m/s and at three values of the ambient temperature - 25^0 C, 35^0 C and 45^o C.

At water speeds of 0.1, 0.2 and 0.3 m/s, the inlet pressure, or rather the pressure drop, remains constant - 1.8 Pa, and the water flow rate was 1.03, 1.06 and 1.09 g/s, with respectively

Table 1 was used to check for the initial data 1 and Figure 2.

A calculation was carried out to determine the surface temperature of PEC (t_p).

1) The equivalent channel diameter is calculated, as follows:

$$d_e = \frac{4F}{P} = \frac{4 \cdot 8 \cdot 8}{4 \cdot 8} = 8 \text{ mm}.$$

Table 1: Photovoltaic thermal battery simulation results using COMSOL Multiphysics 5.6 at different densities of concentrated solar radiation flux.

Flux density supplying solar radiation [W/m^2]	Inlet water speed t_{ww} [m/s]	Ambient temperature $t_{a.}$ °C	Inlet water temperature of Absorber t_1 °C	Outlet water temperature of Absorber t_2 °C	Inco-ming water pressure, Pa	Water flow at the absorber outlet, g/s
800	0,1	25	20	24,6	18,8	1,03
		35	20	34,9		1,03
		45	20	43,0		1,03
1000	0,1	25	20	24,7	18,8	1,03
		35	20	34,9		1,03
		45	20	44,6		1,03
1200	0,11	25	20	39,8	18,8	1,03
		35	20	48,2		1,03
		45	20	60,0		1,03
800	0,2	25	20	22,8	18,8	1,06
		35	20	32,9		1,06
		45	20	43,7		1,06
1000	0,2	25	20	22,9	18,8	1,06
		35	20	33,1		1,06
		45	20	43,8		1,06
1200	0,2	25	20	37,7	18,8	1,06
		35	20	46,4		1,06
		45	20	58,2		1,06
		35	20	31,8		1,09
		45	20	40,9		1,09
1000	0,3	25	20	22,7	18,8	1,09
		35	20	32,9		1,09
		45	20	43,4		1,09
1200	0,3	25	20	36,9	18,8	1,09
		35	20	46,1		1,09
		45	20	57,9		1,09
1000	0,1	25	20	24,6	18,8	1,03
		35	20	34,9		1,03
		45	20	43,0		1,03

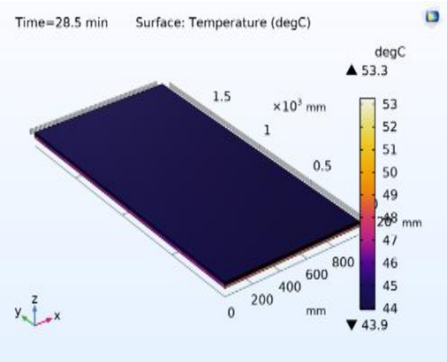

Figure 2: Temperature gradient on the surface of a photoelectric thermal battery made in COMSOL Multiphysics 5.6.

2) Average water temperature determine using:

$$\overrightarrow{t_w}=0{,}5(t_2+t_1)=0{,}5(48{,}2+20)=34{,}1\ ^{\circ}\mathrm{C}.$$

Surface temperature: t_s=45,9 ºC.
Inlet water temperature: t_1=20 ºC.
Outlet water temperature: t_2=48,2 ºC.
Water speed: W=0,1 m/s.
Water flow: G=1,03 g/s=0,00103 kg/s.
Ambient temperature: t_a=35 ºC, at this temperature according to L.2.
Kinematic viscosity: $\mathcal{V}_v=0{,}705\cdot10^{-6}$ m/s.
Density: $\rho_v=993{,}2$ kg/m^3.
Dynamic viscosity: $\mu_v=700{,}2\cdot10^{-6}$ Pa·s.

3) We accept wall temperature t_w=40 ºC.
At this temperature: μ_w=653,3·10-6 Pa·s.

4) Determining temperature using:

$$t_h=0{,}5(t_{wall}+\overrightarrow{t_w})=0{,}5(40+34{,}1)=37^{\circ}\ \mathrm{C}.$$

At this temperature kinematic viscosity:

$$\mathcal{V}_g=0{,}703\cdot10^{-6}\ \mathrm{m/s}.$$

Volume expansion coefficient: $\beta_g=3{,}67\cdot10^{-4}$ 1/K.
Heat capacity of water: C_{pg}=4,174 kJ/kg·ºC.
Prandtl number: P_{pg}=4,69.
Thermal conductivity: λ_g=0,622 W/m·ºC.

5) Determining Reynolds number using:

$$R_e=\frac{W\cdot d_e}{\mathcal{V}_v}=\frac{0{,}1\cdot8{,}0\cdot10^{-3}}{0{,}705\cdot10^{-6}}=1135<2300.$$

therefore the flow regime is laminar.

6) The product of the number Pe (Pecle) and the ratio of the diameter to the length of the channel is determined by

$$\mathrm{Pe}=\frac{d_e}{l}=\frac{4\cdot G\cdot C_{pg}}{\pi\cdot l\cdot\lambda_g}=\frac{4\cdot0{,}00103\cdot4{,}174\cdot10^3}{3{,}14\cdot1{,}95\cdot0{,}622}=4{,}51.$$

The product of the reciprocal of Re and the ratio of the length to the diameter of the channel may be calculated using:

$$\left(\frac{1}{Re}\cdot\frac{l}{d_e}\right)=\frac{1}{1135}\cdot\frac{1950}{8}=0{,}215.$$

Correction for the section of hydrodynamic stabilization my be calculated using:

$$\mathcal{E}=0{,}6\left(\frac{1}{Re}\cdot\frac{l}{d_e}\right)^{-\frac{1}{7}}\cdot\left(1+2{,}5\,\frac{1}{Re}\cdot\frac{l}{d_e}\right)=1{,}148.$$

Channel section: 8x8 mm^2.

7) Rayleigh coefficient (Ra) at temperature $t_г$=37 ºC and is determined using:

$$\mathrm{Ra}=(\mathrm{G}\cdot\mathrm{P_z})_g=g\cdot\beta_g\,\frac{(t_c-\overrightarrow{t_v})\cdot d_e^3}{\mathcal{V}_g^2}\cdot P_{z_g}=$$

$$=9{,}81\cdot3{,}67\cdot10^{-4}\,\frac{(40-34{,}1)\cdot8\cdot10^{-3}}{0{,}703\cdot10^{-6}}\cdot4{,}69=1\cdot10^5<8\cdot10^5.$$

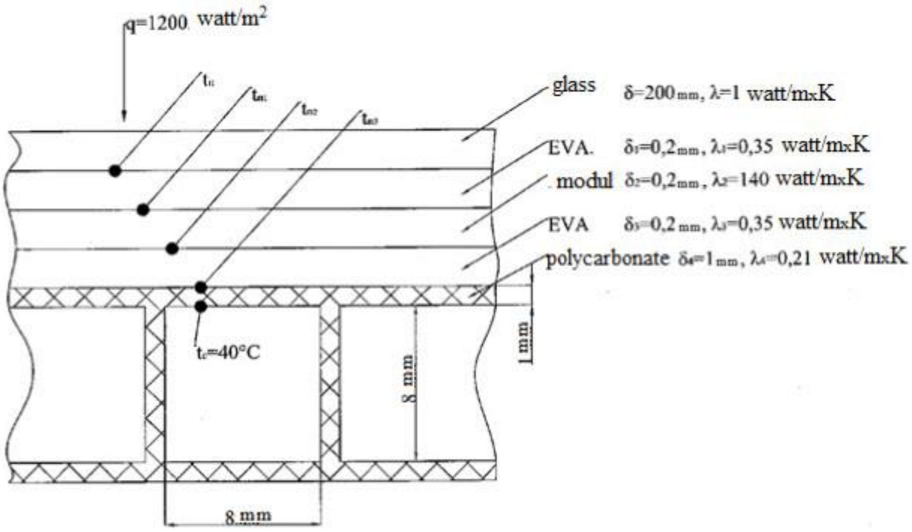

Figure 3: Calculation scheme for determining t_c.

therefore, the flow regime is viscous and according to L.1, it is applicable:

$$\mathrm{Nu_g}=1{,}55\left(Pe_g\frac{d_e}{l}\right)^{\frac{1}{3}}\cdot\left(\frac{\mu_v}{\mu_c}\right)^{0{,}14}\cdot\mathcal{E}=$$

$$=1{,}55(4{,}51)^{\frac{1}{3}}\cdot\left(\frac{700{,}2}{653{,}3}\right)^{0{,}14}\cdot1{,}148=2{,}97.$$

8) The heat transfer coefficient from the inner wall to the water may be calculated using:

$$\alpha=\frac{Nu_g\lambda_g}{d_e}=\frac{2{,}97\cdot0{,}622}{8\cdot10^{-3}}=230{,}9\ \mathrm{W/m^2\cdot h}.$$

9) The temperature of the inner wall of the channel in contact with water. From Newton's formula may be calculated.

10) q=α($t_{wall}-\overrightarrow{t_w}$) we find

$$t_{wall}=\frac{q}{\alpha}+\overrightarrow{t_w}=\frac{1200}{230{,}9}+34{,}1=39{,}3\ ^{o}\mathrm{C}.$$

The resulting temperature of 39.3°C is close to the accepted one - 40°C, and then a calculation is made (Figure 3) to determine the surface temperature of the PEC t_c. The surface temperature t_c PEC is calculated without taking into account glass.

The heat transfer coefficient of a photoelectric panel layer is determined using:

$$K=\frac{1}{\frac{\sigma_1}{\lambda_1}+\frac{\sigma_2}{\lambda_2}+\frac{\sigma_3}{\lambda_3}+\frac{\sigma_4}{\lambda_4}}=\frac{1}{10^{-3}\left(\frac{0{,}2}{0{,}35}+\frac{0{,}2}{140}+\frac{0{,}2}{0{,}35}+\frac{1}{0{,}21}\right)}=169{,}3\ \mathrm{W/m^2\cdot K}.$$

From Newton's formula $q=\kappa\ (t_c-t_{wall})$ we deterine the temperature t_c of the PEC surface:

$$t_c=\frac{q}{\kappa}+t_{wall}=\frac{1200}{169{,}3}+39{,}3=7{,}09+39{,}3=46{,}4\ ^{o}\mathrm{C}.$$

The calculated temperature t_c= 46.4°C is close to the temperature obtained by COMSOL t_c= 45°C.

The agreement between the COMSOL calculation and the heat transfer equations indicates that the COMSOL program is working correctly.

Similar calculations, taking into account the actual water consumption may be calculated using:

$$G=W\cdot f\cdot\rho=0{,}1\cdot0{,}785\cdot d_e^2\cdot995==0{,}005\ \mathrm{kg/s},$$

show that the surface temperature t_c PEC is 35-36°C and the water temperature at the outlet is ≈30°C.

4 CONCLUSIONS

A mathematical model of a photoelectric thermal battery, consisting of a photoelectric module and an absorber (heat converter) made of a polymer material, is proposed. The mathematical model of the PEC-TEC installation was implemented using the COMSOL Multiphysics 5.6 program and can be used to solve problems of hydrodynamics and heat transfer.

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