Results of Study of Photovoltaic Thermal Battery Based on Thin-Film Module by Modeling and Computational Methods

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Abstract: This article presents the results of model studies of a photovoltaic thermal battery (PVTB) based on a thin-film cadmium telluride (CdTe) module depending on the influence of environmental parameters: solar radiation, air temperature, wind speed on the heating temperature of PVTB elements. A heat transfer scheme in PVTB elements, a mathematical model of heat balance processes and a program in the algorithmic Python language for calculating thermal and energy parameters were developed. The equations of thermal balances were solved in the static state of the installation using the numerical method of Gauss-Seidel iterations. To validate the model, the calculated simulation results were compared with experimental data. A comparison of the values of the corresponding parameters is presented in graphical images. The adequacy of the model was verified by the method of "assessment of agreement and standard deviation". The following values of RMSE and determination coefficients were calculated for the parameters, respectively, for the temperature of the photovoltaic cell, liquid and electrical efficiency R2=0.88, for thermal efficiency and power R2=0.99, for power RMSE=2.56 W, RMSE deviation 5.72%. Using the SolidWorks Flow Simulation software was performed CFD PVTB modeling, simulating the temperature dynamics of glass, PV and absorber depending on environmental factors and the temperature dynamics of cooling water circulating in a copper heat exchanger. The values of the parameters obtained from CFD modeling correspond to the experimental data. The considered modeling methods make it possible to calculate the thermal and energy parameters of PVT installations at the engineering design stage.

1 INTRODUCTION

Solar energy is a potential source for the production of environmentally electrical and thermal energy. Usually photovoltaic modules (PV) convert about 15-20% of solar energy into electrical energy the remaining 80-85% of the energy is dissipated into heat. As a result of heat accumulation, the PV will begin to lose efficiency and productivity. The use of photovoltaic thermal batteries (PVTB) technology is an acceptable way for cooling of PV and using the accumulated heat to generate heated water [1], [2], [3], [4], [5], [6]. PVTB, by removing heat through the circulation of liquid through a thermal battery, cooling of PV and increase the efficiency of solar energy conversion and also simultaneously produce electrical energy and heated water. PVT research focuses on technology development for improve design solutions and the efficiency of solar energy conversion [7], [8], [9]. Reducing the cost of installations and the cost of a unit of energy produced is an important task of photovoltaic thermal installation technology. To perform such tasks, we have developed a PVTB design based on CdTe thin-film modules. In this paper is considered mathematical and CFD modeling of the calculation of thermal and energy parameters of the PVTB.

2 METHODOLOGY

The thermal and energy parameters of PVT can be calculated using modeling. For this will develop a scheme of thermal processes in PVT battery layers and a mathematical model. Will write the heat balance equations for each PVTB layer depending on environmental factors: solar radiation, ambient temperature, wind speed, geometric and thermo-physical properties of materials, liquids. The assumptions and limitations made during the development of mathematical and CFD modeling as follows:

- heat is not lost at the edges of PVTB;
- the thermo-physical properties of the materials remain constant over the area;
- the effect of dust or partial shading is not taken into account;
- the fluid flow rate is constant, 0.002 kg/s.

The initial temperature of the liquid at the inlet at time t=0 is T_{in} =20°C. The PVTB installation consists of a CdTe-based thin-film PV technology and a thermal battery in the form of a "sheet-tube" structural assembly. An absorber made of aluminum sheet in the form of a box is attached to the back side of the PVM, inside which heat-exchange copper tubes covered with thermal insulation material are placed. The "sheet-pipe" design of the PVTB is shown in Figure 1.

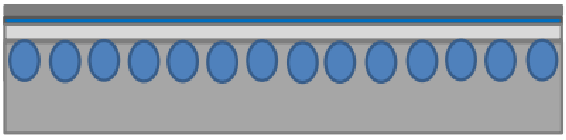

Figure 1: Cross-section of the PVTB "sheet-tube" design.

The research of the authors of these works relates to the development of a model of the PVTB, which can assess the suitability of various design parameters in any environmental conditions, which can lead to improved performance of the modules. Various configurations of PVTB have been developed and their performance characteristics have been studied depending on the optical, geometric and thermo-physical properties of materials, type of liquid, wind speed and direction, solar radiation and ambient temperature.

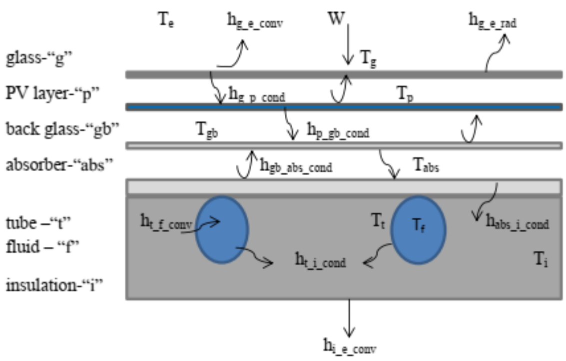

Figure 2: Scheme of heat transfer coefficients in PVTB layers according to the "sheet-pipe" design in the section.

The name of the designations in the scheme in Figure 2 as follow:

$h_{g\_e\_conv}$ – coefficient of convective heat transfer from the front glass to the environment, $h_{g\_e\_rad}$ – coefficient of radiative heat transfer between the front glass and the environment, $h_{g\_p\_cond}$ - heat transfer coefficient between the front glass and the photovoltaic layer, $h_{p\_gb\_cond}$ - heat transfer coefficient between the photovoltaic (PV cell) layer and the back glass, $h_{gb\_abs\_cond}$ - heat transfer coefficient between the rear glass and the absorber, $h_{abs\_i\_cond}$ - heat transfer coefficient between absorber and insulation, $h_{t\_f\_conv}$ – coefficient of convective heat transfer between tube and fluid, $h_{t\_i\_conv}$ – heat transfer coefficient between absorber and insulation, $h_{i\_e\_conv}$ - coefficient of convection between insulation and the environment, W – the density of the solar radiation flux incident on the front surface of the glass, T_e – temperature of environment or ambient-Ta, T_g -front glass temperature, T_p - temperature of the photoelectric layer, T_{gb} – rear glass temperature, T_{abs} – absorber temperature, T_t – tube temperature, T_f – fluid temperature, T_i – insulation temperature, T_{sky} – equivalent radiation temperature of the sky.

2.1 Mathematical Modeling

The mathematical model is based on the heat transfer processes described in Figure 2. The equations of thermal balances for the elements of the PVTB will write down. Similar processes were modeled in [10], [11], [12]. As is known from thermal engineering and solid state physics, when heat is applied to a body, its internal energy changes, which is described by the following:

$$Mc\frac{dT}{dt} = \frac{dU}{dt}.$$

M- body weight, kg; *c* – body heat capacity, J/kg, K; *T* - body temperature, K; *U* - internal energy of the body, J.

Thermal balance between the front glass and the photovoltaic (PV) layer:

$$\begin{aligned} M_g c_g \frac{dT_g}{dt} &= h_{g-e-conv} S_g (T_e - T_g) \\ &+ h_{g-e-rad} S_g (T_{sky} - T_g) \\ &+ h_{g-p-cond} S_g \\ &(T_p - T_g) + +S_g \alpha_g W. \end{aligned} \quad (1)$$

From (1) it is possible to express the temperature of the front glass (2):

$$T_g = \frac{h_{g-e-conv}T_e + h_{g-e-rad}T_{sky} + h_{g-p-cond}T_{p+} \alpha_g W}{h_{g-e-conv} + h_{g-e-rad} + h_{g-p-cond}}, (2)$$

where:

$$h_{g-e-conv}=\begin{cases}5{,}7+3{,}8\cdot v_w\,, \text{для } v_w<5\text{ м}/c\\ 6{,}47+v_w^{0{,}78}\,, \text{для }\ v_w\ \geq 5\text{ м}/c\end{cases}$$

$$h_{g-e-rad}=\varepsilon_g\cdot\sigma\left(T_g^2+T_{sky}^2\right)\left(T_g+T_{sky}\right),$$

where:

$$T_{sky}=0{,}00552\cdot T_e^{1{,}5}$$

$$h_{g-p-cond}=\frac{1}{\frac{\delta_g}{k_g}+\frac{\delta_p}{k_p}}$$

ε_g- glass emissivity coefficient, 0,88; δ_g –thickness of glass, 0,0032 m and δ_p - thickness of PV, 0,0004 m, σ – Stefan-Boltzmann constant, $5{,}67\cdot10^{-8}\ W/m^2\cdot K^4$, $S_g, S_{gb}, S_p, S_{abs}$ - areas of the front, rear glass, PV layer, absorber, 0,72 m^2,

$$h_{g-p-rad}=\frac{1}{\frac{1}{\varepsilon_g}+\frac{1}{\varepsilon_p}-1}\cdot\sigma\left(T_g^2+T_p^2\right)\left(T_g+T_p\right),$$

where: ε_p- the emissivity coefficient of the PV layer, 0,10; $(\alpha\tau)_p$-absorption and transmission coefficient of solar radiation of the PV layer, $\alpha=0{,}9$; $\tau=0{,}93$; η_{el} – electrical efficiency of the PV layer;

$$\eta_{el}=\eta_{stc}\left[1-\beta_p\left(T_p-T_{stc}\right)\right].$$

The equation of the thermal balance between the PV layer and the rear glass:

$$M_pc_p\frac{dT_p}{dt}=h_{p-g-cond}S_p\left(T_g-T_p\right)+ +h_{p-gb-cond}S_{gb}\left(T_{gb}-T_p\right)+(\alpha\tau)_p\cdot S_p\cdot W\left(1-\eta_{el}\right). \quad (3)$$

From (3) express:

$$T_{gb}=\frac{h_{g-p-cond}T_p+h_{gb-abs-cond}T_{abs}}{h_{gb-p-cond}+h_{gb-abs-cond}}, \quad (4)$$

$$h_{p-g-cond}=h_{p-gb-cond},$$

$$h_{p-g-cond}=h_{p-gb-cond}=\frac{1}{\frac{\delta_{gb}}{k_{gb}}+\frac{\delta_p}{k_p}}.$$

The equation of thermal balance between the rear glass and the absorber:

$$M_{gb}c_{gb}\frac{dT_{gb}}{dt}=h_{gb-p-cond}S_{gb}\left(T_p-T_{gb}\right)+ h_{gb-abs-cond}S_{gb}\left(T_{abs}-T_{gb}\right). \quad (5)$$

From (5) express:

$$T_{gb}=\frac{h_{g-p-cond}T_p+h_{gb-abs-cond}T_{abs}}{h_{gb-p-cond}+h_{gb-abs-cond}}, \quad (6)$$

where: $h_{gb-abs-cond}=\frac{1}{\frac{\delta_{gb}}{k_{gb}}+\frac{\delta_{abs}}{k_{abs}}}$,

k_g, k_{gb}, - thermal conductivity of glases, 1,1 W/m·K and k_p - thermal conductivity of PV,140 W/m·K.

Heat balance equation between absorber and tube:

$$M_{abs}c_{abs}\frac{dT_{abs}}{dt}=h_{abs-t-cond}S_{abs-t}(T_t- -T_{abs})+h_{abs-i-cond}S_{abs-i}(T_a-T_{abs})+ +h_{abs-gb-cond}S_{abs}\left(T_{gb}-T_{abs}\right) \quad (7)$$

From (7) express:

$$T_{abs}=\frac{h_{abs-t-cond}S_{abs-t}T_t+h_{abs-i-cond}S_{abs-i}T_a+h_{abs-gb-cond}S_{abs}T_{gb}}{h_{abs-t-cond}S_{abs-t}+h_{abs-i-cond}S_{abs-i}+h_{abs-gb-cond}S_{abs}} \quad (8)$$

$$h_{abs-t-cond}=\frac{1}{\frac{\delta_{abs-t}}{2k_{abs-t}}}$$

$$\delta_{abs-t}=\frac{X-D_{ext}}{4}$$

$$S_{abs-t}=\delta_{abs}L$$

k_{abs-t} - thermal conductivity of the absorber, 237 W/m·K; δ_{abs}- thickness of the absorber, 0,0006m; L - the length of the absorber,10,5 m; X is the pitch of the tube arrangement, 0,058 m,

$$h_{abs-i-cond}=\frac{1}{\frac{\delta_{abs-i-cond}}{2k_{abs-i-cond}}}$$

$$S_{abs-i}=S_{abs}\left(\frac{W1-D_{ext}}{W1}\right)$$

$$h_{abs-gb-cond}=\frac{1}{\frac{\delta_{gb}}{k_{gb}}+\frac{\delta_{abs}}{k_{abs}}}$$

The equation of the thermal balance between the tube and the coolant-fluid:

$$M_tc_t\frac{dT_t}{dt}=h_{t-f-conv}S_{t_{int}}\left(T_f-T_t\right)+ +h_{t-abs-cond}S_{abs-t}(T_{abs}- -T_t)+h_{t-i-cond}S_{t\_i}(T_i-T_t) \quad (9)$$

$$h_{t-f-conv}=\frac{Nu_fk_f}{D_{t.in}},$$

From (9) express:

$$T_t = \frac{h_{t-f-conv}S_{t\_int}T_f + h_{t-abs-cond}S_{abs-t}T_{abs} + h_{t-i-cond}S_{t\_i}T_i}{h_{t-f-conv}S_{t\_int} + h_{t-abs-cond}S_{abs-t} + h_{t-i-cond}S_{t\_i}} \quad (10)$$

where Nu_f – Nusselt number; $D_{t.in}$ – inner diameter of the tube, m.

$$Nu_f = 4.36,\ Re_f \le 2300,$$
$$Nu_f = 0.023(Re_f^{0.8}Pr_f^{0.4}),\ Re_f > 2300,$$

Re - Reynolds number; *Pr*- Prandtl number.

$$h_{abs-t-cond} = \frac{1}{\frac{\delta_t}{2k_t}},$$

$h_{t-i-cond} = \frac{1}{\frac{\delta_i}{2k_i}}$ by, $\delta_i \gg D_{t.ext}$, δ_t, δ_i – tube wall thickness and insulation layer, m; k_t and k_i- thermal conductivity coefficients of the tube and insulation material; $D_{t.ext}$ – external diameter of the tube, m.

$S_{t\_i} = (\frac{\pi}{2} + 1)D_{t.ext}L$ –internal area of the tube, m^2

The equation for the coolant (fluid):

$$M_f c_f \frac{dT_f}{dt} = h_{t-f-conv}S_{t\_int}\left(T_t - T_f\right) - \dot{m}_f c_f (T_{fout} - T_{fin}), \quad (11)$$

$$T_f = 0.5(T_{fout} + T_{fin}),$$

$$h_{t-f-conv} = \frac{Nu_f k_f}{D_{t.in}},$$

Thermal balance equation of the insulation layer:

$$M_i c_i \frac{dT_i}{dt} = h_{abs-i-cond}S_i(T_{abs} - T_i) + h_{t-i-cond}S_{t\_i}(T_t - T_i) + h_{i-e-conv}S_i(T_e - T_i) \quad (12)$$

From (12) express:

$$T_i = \frac{h_{abs-i-cond}S_iT_{abs} + h_{t-i-cond}S_{t\_i}T_t + h_{i-e-conv}S_iT_e}{h_{abs-i-cond}S_i + h_{t-i-cond} + h_{i-e-conv}S_i} \quad (13)$$

$$h_{i-e-conv} = \begin{cases} 5{,}7 + 3{,}8 \cdot v_w \text{ , для } v_w < 5\ m/s \\ 6{,}47 + v_w^{0{,}78} \text{ , для } \ v_w \ge 5\ m/s \end{cases}$$

$$h_{t-i-cond} = \frac{1}{\frac{\delta_{abs-i-cond}}{2k_{abs-i-cond}}}$$

$$h_{abs-i-cond} = \frac{1}{\frac{\delta_{abs-i-cond}}{2k_{abs-i-cond}}}$$

$$S_{t\_i} = (\frac{\pi}{2} + 1)D_{t.ext}L,$$

The thermal efficiency of the installation can be calculated by the following expression:

$$\eta_{th} = \frac{\dot{m}_f c_f (T_{fout} - T_{fin})}{S_{pvtb}W},$$

where, $\dot{m}_f$ – fluid flow rate, 0,002kg/s; c_f – heat capacity of the fluid, 4180J/kg K; T_{fout} – temperature of the fluid at the inlet to the battery, K; T_{fin} - temperature of the fluid at the outlet of the battery, 273,15 K. According to formulas respectively, the changes in the electrical and thermal efficiency of the PVTB were calculated, the values of which are derived in the form of graphs of graphs depending on T_r - the specific temperature decrease relative to the solar radiation flux density, which is expressed as follows.

$$T_r = \frac{T_{fin} - T_a}{W},$$

where, T_a – temperature of ambient.

3 RESULTS AND DISCUSSIONS

According to this mathematical model, a program was compiled in the algorithmic Python language (Spider 3.8.10-version) to calculate the corresponding parameters of thermal processes of HTP. Using the values of environmental parameters and some thermal parameters, geometric dimensions, the program solved the system of equations from (1) to (13) numerically using the Gauss Seidel iteration method and found the temperature values T_g, T_p, T_{abs}, T_f of the corresponding layers and the energy parameters of PVTB. According to the calculated simulation data, graphs of the corresponding parameters were plotted in Figure 3-7.

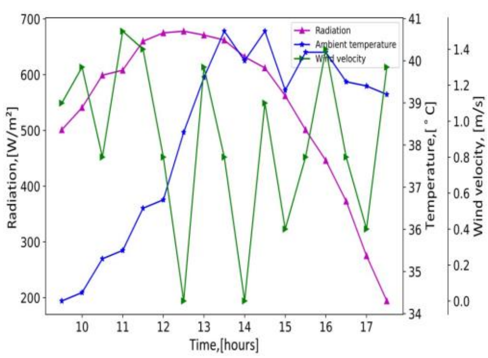

Figure 3: Ambient parameters.

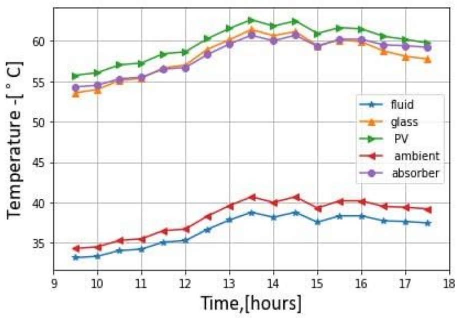

Figure 4: Temperature dynamics.

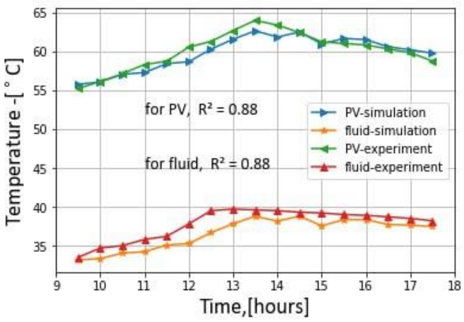

Figure 5: Comparison of values of modeling and experimental temperatures.

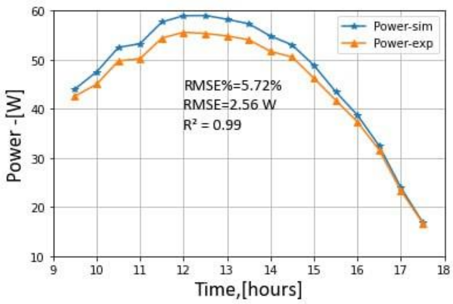

Figure 6: Comparison of values of modeling and experimental powers.

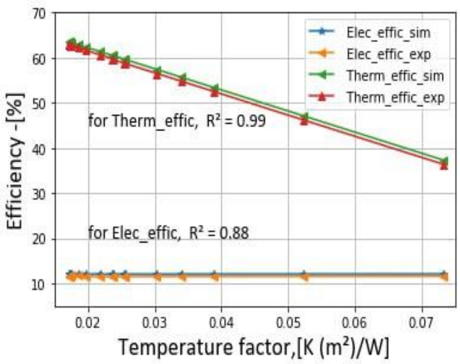

Figure 7: Graphs of efficiency.

Model were out validate with the experimental data by the temperatures, powers, efficiency of the PVTB of July 27, 2022. The accuracy of the proposed model at each verification level was evaluated using the methods of "agreement and Root Mean Square Error (RMSE) estimation". Therefore, we use a general analysis based on the coefficient of determination (R^2) and RMSE.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(P_{e_i} - P_{m_i})}{\sum_{i=1}^{n}(P_{e_i} - \bar{P}_{e_i})}$$

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_{e_i} - P_{m_i}\right)^2}{n}} \text{ or}$$

$$\text{RMSE\%} = \frac{\sqrt{\frac{\sum_{i=1}^{n}\left(P_{e_i} - P_{m_i}\right)^2}{n}}}{\frac{\sum_{i=1}^{n} P_e}{n}} \cdot 100\%$$

where: n - number of measured data; P_e and P_m- electric power of the PVTB, experimental and simulation-based model; $\overline{P_e}$ - the average power value determined by the experiment. Comparison of results were out by RMSE and coefficient of determination and is R2 =0,88…0,99.

4 CFD MODELING

For researching and engineering estimates of PVT installations is we execute a CFD(Computational Fluid Dynamics) simulation for analysis of the temperature distribution in the elements of the same PVTB, which studied by experiments and modeling. Using the SolidWorks.2020.SP1.0, Flow Simulation software, CFD calculation of the temperature of the layers of the PVTB structure and the coolant-water at the exit from the thermal battery was performed. This program makes it possible to predict the performance of the structure, allows calculations at different values of input parameters. The program makes it possible to avoid numerous experiments and make accurate measurements. CFD calculation data can be used to create prototypes of the PVT structure and evaluate these structures at the project implementation stage and save time and finances. CFD calculation also allows optimization of the design parameters and operation of the prototype during its testing. The figures show the results of the CFD analysis in solar flux density 800W/m^2, mass flow rating of fluid 0.002 kg/s.

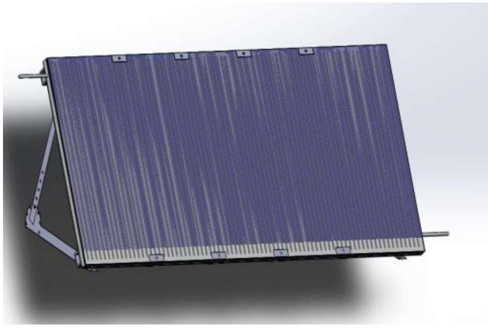

Figure 8: 3D drawing of PVT battery.

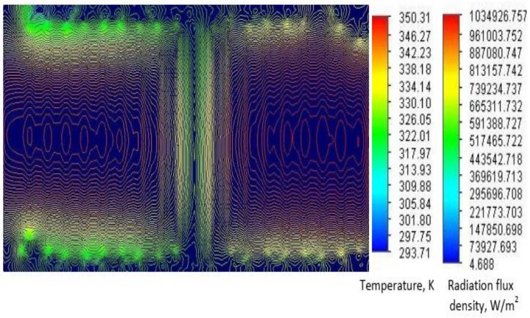

Figure 9: Temperature dynamics of glass.

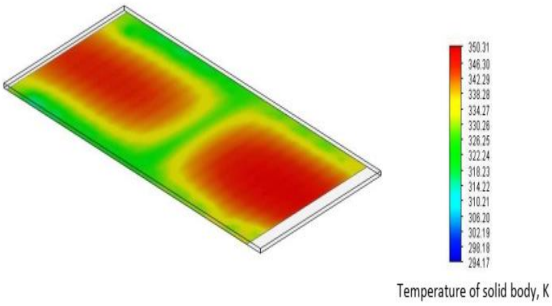

Figure 10: Temperature dynamics of absorber.

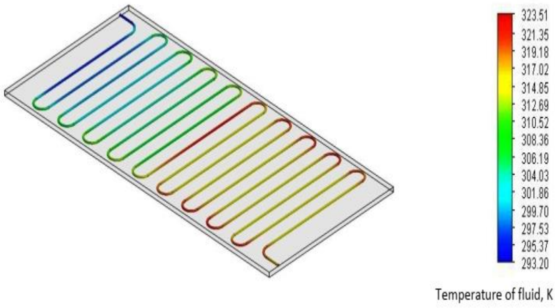

Figure 11: Temperature dynamics of water.

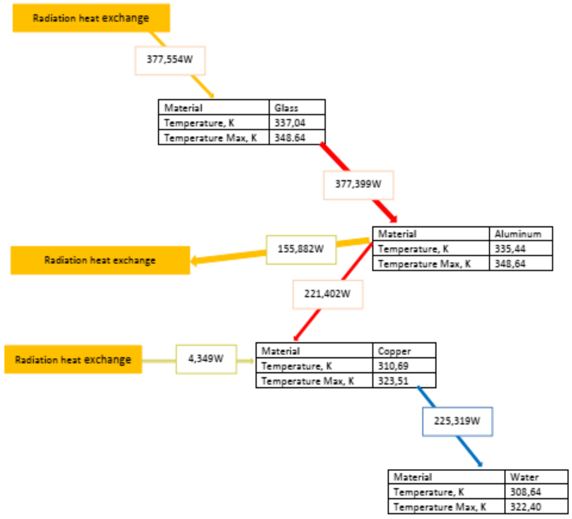

Figure 12: Temperature distribution in PVTB elements.

In Figures 8-12 presented dynamics of temperatures in elements of PVTB. Changes of values of temperature by materials give in Table 1. Average values of the temperature of the elements of the PVTB at the peak time of the sunshine obtained by the calculation correspond to the temperature values obtained by the mathematical model and experimental results.

Table 1: Temperature values of PVTB elements.

Materials	Temperature		Temperature Max,	
	K	^{0}C	K	^{0}C
Glass of PV	337,04	63,89	348,64	75,49
Aluminum plate (absorber)	335,44	62,29	348,64	75,49
Copper (tube exchanger)	310,69	37,54	323,51	50,36
Fluid (water)	308,64	35,49	322,40	49,25

5 CONCLUSIONS

According to the mathematical model, a program was written in the algorithmic Python language, according to which calculations were carried out by the numerical method of the corresponding parameters. The calculated values of temperature changes across the layers of the PVTB structural elements, power, thermal and electrical efficiency of the installation are shown graphically. Comparison the values of a few parameters calculated by simulation with experimental data showed the reliability of the model with a determination coefficient by power, thermal efficiency is 0,99, temperature, electrical efficiency and fluid is 0.88. This model will be used to calculate the energy and thermal parameters of the PVTB for climatic conditions of different geographical areas. CFD model also easy for calculate of temperatures of elements of PVT installations.

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