1. Artur BUGAŁA[1], 2. Antoni ARENDACZ[1], 3. Dorota BUGAŁA[1]

[1]Politechnika Poznańska, Instytut Elektrotechniki i Elektroniki Przemysłowej
ORCID: 1. 0000-0002-3321-4545; 3. 0000-0002-2579-448X

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Simulation analysis of a photovoltaic-thermal energy generator for residential prosumers in Matlab/Simulink

Streszczenie. *Niniejsza praca dotyczy analizy funkcjonowania zintegrowanego generatora energii elektrycznej i cieplej, która została przeprowadzona w programie MATLAB/SIMULINK uwzględniając zmienność parametrów zewnętrznych w postaci irradiancji oraz temperatury otoczenia. Kolektor hybrydowy został połączony z hydrauliczną częścią obiegu wody, modelując w ten sposób jej odbiór z jego wymiennika i doprowadzenie do zasobnika wody o pojemności 250 l z możliwością wykorzystania przez użytkownika. W pracy wykorzystano kolektor o mocy elektrycznej i cieplnej odpowiednio 300 W i 450 W. Przedstawiono relacje występujące pomiędzy aktualnie generowaną mocą elektryczną, temperaturą w zbiorniku i wymienniku kolektora z uwzględnieniem poziomu strat ciepła w trakcie działania całego systemu. Zwrócono uwagę na osiągane wartości sprawności elektrycznej, cieplnej i całkowitej przy zmianie warunków słonecznych. (**Analiza symulacyjna fotowoltaiczno-cieplnego generatora energii dla prosumentów mieszkaniowych w programie Matlab/Simulink**).*

Abstract*. The paper concerns the analysis of an integrated electricity and heat generator, which was carried out in the MATLAB/SIMULINK program, taking into account the variability of external parameters in the form of irradiance and ambient temperature. The hybrid collector has been connected to the hydraulic part of the water circuit, thus modeling its collection from the exchanger and supplying the medium to a water tank with a capacity of 250 l, which can be used by the user. A collector with an electric and thermal power of 300 W and 450 W has been modeled. The relationships between the currently generated electrical power, the temperature in the tank and the collector exchanger, taking into account the level of heat losses during the operation of the entire system, were presented. The values of electrical, thermal and total efficiency for different solar conditions are presented.*

Słowa kluczowe: hybrydowy kolektor PV/T, energia słoneczna, kogeneracja energii, sprawność termiczna, ogniwo fotowoltaiczne
Keywords: hybrid PV/T collector, solar energy, energy cogeneration, thermal efficiency, solar cell

Introduction

The energy of solar radiation can be used to generate electricity, heat or simultaneously to generate both forms of energy. A hybrid photovoltaic-thermal (PV/T) generator is described by electrical, thermal and total efficiency. For this purpose, those devices integrate photovoltaic cells, absorbers and heat exchangers. The thermal energy received in the collector allows reduction of the temperature of the photovoltaic cells, leading to an increase in the open circuit voltage and a voltage at the maximum power point, which leads to an increase in the electric power. This fact was emphasized in [1]. Removed heat accumulated in photovoltaic module can be reused in different more appropriate way. The high temperature of the cells, on the other hand, accelerates their degradation. It should be emphasized that in a photovoltaic-thermal collectors there is a temperature gradient along the absorber, therefore not all solar cells may operate with the same electrical characteristics due to their temperature coefficient. This can lead to a current mismatch between individual cells, leading to a reduction in the generated electrical power. Optimal thermal and electrical configuration of hybrid collectors was discussed in [2].

In [3], the authors compared the results of the electric, thermal and total efficiency of a hybrid water collectors based on the analysis of 23 publications from 2011 to 2017. It has been shown that PV and thermal efficiency of PV/T collectors ranges from 1.5% to 28% and 23% to 75%, respectively.

A critical assessment of the impact of climatic, design and operational factors on the thermal, electrical, and overall efficiency of PV/T systems was performed in [4]. The authors stated that the thermal efficiency decreases with increasing values of inlet temperature, duct length, channel depth, thermal resistance, ambient temperature, and mass flow rate and increases with the increasing values of the solar irradiance, tilt angle close to latitude angle, numer of air inlets and using diffuse reflectors and solar tracking systems.

Figure 1 shows a view of a device that is a combination of a photovoltaic and thermal generator.

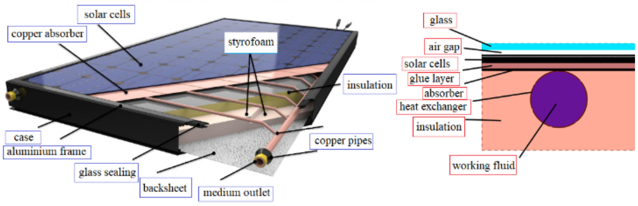

Fig. 1. Components of the PV/T collector [5]

Depending on the type of a medium used to receive heat energy from the photovoltaic part, PV/T collectors are distinguished [6][7]:

- air - the stream of flowing air receives thermal energy from the absorber and is heated, the channel in which the heated air flows can be located under the PV module as well as above it,
- water - water flowing in the formed exchanger is used as the working medium,
- water-air - the combination of two solutions is designed to eliminate problems associated with the independent operation of each of them, the operation of the collector can be controlled to switch between hot water and air.

In many applications, air hybrid collectors are used, characterized by lower construction and operating costs. Various types of PV/T air collectors with their detailed mathematical description are presented in [8].

Hybrid collectors can be divided into different categories, as shown in the figure 2.

PV/T collectors are used as a source of hot water in residential buildings, both in single-family and multi-family houses, and as a source of space heating. Heating can be provided in conjunction with a heat pump or booster heaters. Application of PV/T collectors in water heating for residential and office buildings including innovative coolants is presented in [10].

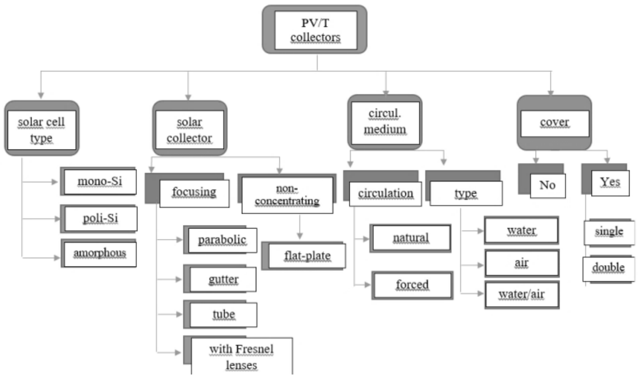

Fig. 2. Criteria categories for PV/T collectors [9]

Circuit model of a photovoltaic cell

An integral part of a hybrid collector is a system of photovoltaic cells connected in series. In order to model a section of photovoltaic cells, a single-diode or two-diode circuit model can be used. The single diode model is described by an exponential equation with five parameters: diode saturation current I_o, series R_s and shunt R_b resistances, junction quality factor and electric current I_{ph} proportional to the solar radiation incident on the surface of the cell. Figure 3 shows a single-diode equivalent model of a photovoltaic cell.

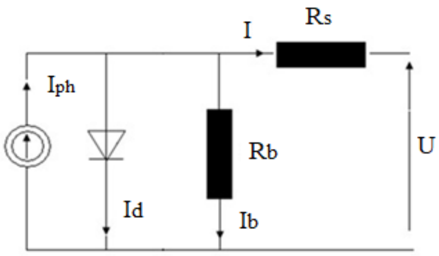

Fig. 3. Single-diode equivalent model of a photovoltaic cell [11]

According to Kirchhoff's current law, the solar cell output current can be described as:

(1) $$I = I_{ph} - I_d - I_b$$

Current generated as a result of the internal photovoltaic effect [11]:

(2) $$I_{ph} = I_{sc} \cdot \left(\frac{S}{1000}\right) + J_o \cdot (T - T_{odn})$$

where: S – instantaneous solar radiation power density, T – photovoltaic cell temperature, T_{odn} – temperature for standard test conditions, J_o – current temperature coefficient.

Diode current in the equivalent circuit [12]:

(3) $$I_d = I_o \cdot [\exp(\frac{q \cdot (U + R_S \cdot I)}{\alpha \cdot k_B \cdot T}) - 1]$$

Current flowing through the shunt resistance:

(4) $$I_b = \frac{U + R_S \cdot I}{R_b}$$

where: R_s - series resistance, U - voltage drop on load R, R_b – shunt resistance, α - diode quality factor, k_B - Boltzman's constant.

The introduction of the first and second diode is associated with the presence of the diffusion and recombination components of the dark current:

(5) $$I = I_{ph} - I_{d1} - I_{d2} - I_b$$

Taking into account the dependencies characteristic for the single-diode model with simultaneous modification of the equation to the two-diode circuit:

(6)
$$I = I_{sc} \cdot \left(\frac{S}{1000}\right) + J_o \cdot (T - T_{odn}) - I_{o1} \cdot \left[\exp\left(\frac{q \cdot (U + R_S \cdot I)}{\alpha_1 \cdot k_B \cdot T}\right) - 1\right] - I_{o2} \cdot \left[\exp\left(\frac{q \cdot (U + R_S \cdot I)}{\alpha_2 \cdot k_B \cdot T}\right) - 1\right] - \frac{U + R_S \cdot I}{R_b}$$

Due to the entangled form of the equation, its solution requires a series of iterations according to the relation [11]:

(7) $$I_{i+1} = I_i - \frac{f(I_i, U)}{\frac{df}{dI}(I_i, U)}$$

(8) $$I_{i+1} = I_i - \frac{f(I_i, U)}{-x_1 - x_2 - \frac{R_S}{R_b} - 1}$$

where:

(9) $$x_1 = I_{o1} \cdot \frac{R_S}{\alpha_1 \cdot k_B \cdot T} \cdot \exp(\frac{q \cdot (U + R_S \cdot I)}{\alpha_1 \cdot k_B \cdot T})$$

(10) $$x_2 = I_{o2} \cdot \frac{R_S}{\alpha_2 \cdot k_B \cdot T} \cdot \exp(\frac{q \cdot (U + R_S \cdot I)}{\alpha_2 \cdot k_B \cdot T})$$

Thermal phenomena in a hybrid collector

An important parameter of a photovoltaic-thermal generator is its thermal efficiency.

The amount of solar energy converted into heat depends on the level of irradiance recorded in the collector plane and the level of total losses. Losses are the result of heat exchange between the device and its surroundings, as well as between its individual internal components. Heat transfer occurs in three ways as conduction, convection and radiation. All these mechanisms affect the thermal efficiency of the collector. The heat exchange processes in the device are shown in Figure 4.

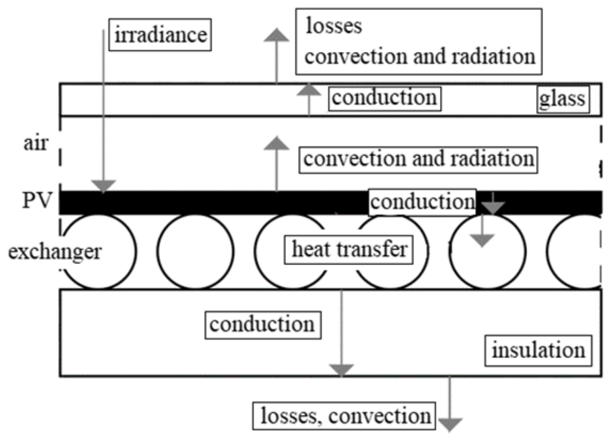

Fig. 4. Heat exchange processes in a hybrid collector

The heat absorbed by photovoltaic cells can be described by the relationship:

(11) $$E_c = \tau_g a_{PV} S$$

where: E_c - absorbed heat, τ_g - transmissivity of the collector glazing, α_{PV} - absorptiveness of PV cells, S - irradiance.

Radiation losses from the collector glazing:

(12) $$\dot{q}_{12} = k_B A_1 [\varepsilon_1 T_1^4 - a_{1\leftarrow 2} T_1^4]$$

where: k_B - Boltzman's constant, A_1 - surface area of the body, ε_1 - emissivity, α - absorptiveness, T_1 - temperature of the emitting body.

In order to determine the heat taken over by the flowing medium, the nature of its flow should be determined by calculating the Reynolds number:

$$Re = \frac{\overline{v_x} D \rho}{\mu} \tag{13}$$

where: $\overline{v_x}$ – average flow velocity, D - channel internal diameter, ρ – medium density, μ - fluid viscosity.

Heat transfer coefficient, which allows to determine the heat flux density [13]:

$$\alpha = \frac{48}{11}\frac{\lambda}{D}\left(\frac{\mu_{\overline{T}}}{\mu_{T_W}}\right)^{0,14} \tag{14}$$

$$\check{q} = \alpha(T_w - \overline{T}) \tag{15}$$

where: α - heat transfer coefficient, λ – conduction coefficient of the exchanger walls, μ_T - viscosity at water temperature, μ_{Tw} - viscosity at exchanger wall temperature, T_w – wall temperature, $\overline{T}$ – water temperature.

The amount of thermal energy transferred to the working medium depends on the arrangement of photovoltaic cells in the module structure. Due to the gaps present between the cells, part of the radiation goes directly to the collector absorber [14]:

$$p = \frac{A_{PV}}{A_c} \tag{16}$$

where: p - module coverage density with photovoltaic cells, A_{PV} - surface area covered by solar cells, A_c - collector surface area.

Taking into account the area covered by solar cells, the heat entering the working medium can be described by the relationship [14]:

$$Q = A_c\left[\frac{\lambda_p}{d_p}\left(\overline{T}_c - T_w\right) + (1-p)S\tau_g\tau_p a_r\right] \tag{17}$$

where: τ_p – transmittance of the absorber's coating, τ_g – transmittance of the glazing, α_r - absorber's absorptiveness.

Simulation model of a PV/T collector

The simulation analysis of the installation operation equipped with a PV/T collector was carried out using the MATLAB/SIMULINK. The structure of the modeled collector is shown in Fig. 4. The simulation model consists of four main sections:

- electric - marked in blue, consists of a solar cells model and a load subsystem. The section models the operation of the PV module, which is an integral part of the collector. It allows to measure current and voltage in order to determine the generated electrical power,
- thermal - marked in orange. The section models the heat exchange between the collector and the environment, as well as between the components of the device,
- liquid - marked in yellow, models heat reception by the network water in the system. It consists of a pipeline, a tank, pumps, an external water source and its collection,
- optical - has implemented functions that calculate reflection, absorption and light transmission coefficients through the glazing layer. It performs calculations of the energy absorbed by the glass and by the PV cells.

Mathematical relationships related to energy exchange processes were implemented based on the analysis of selected publications [13-17], electrical aspects [11][18], optical properties [19-22].

Figure 5 shows a model of a photovoltaic-thermal collector with subsystems.

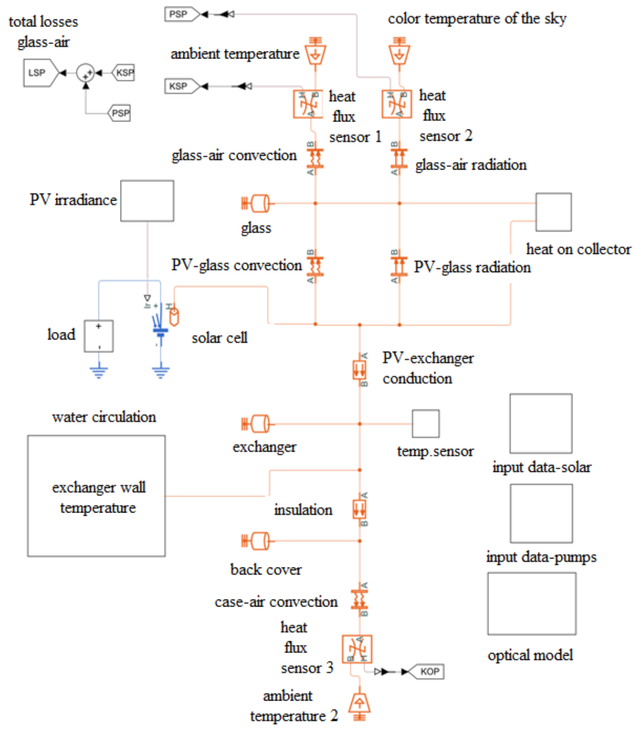

Fig. 5. PV/T collector model developed in the Matlab/Simulink environment

The "*input data-solar*" subsystem contains information on the irradiance values and variability, the angle of incidence of the solar radiaton. The "*input data-pumps*" subsystem contains information on the set flows of pumps pumping the liquid in the system. This section defines the parameters of the collector's internal circulation (operation of the circulation pump, enabling the collection of heat from the collector), demand (hot water consumption by the user) and the parameters of the inflow supplementing water in the tank from an external source. Fig. 6 shows the flow variability curves for the pump section during the simulation.

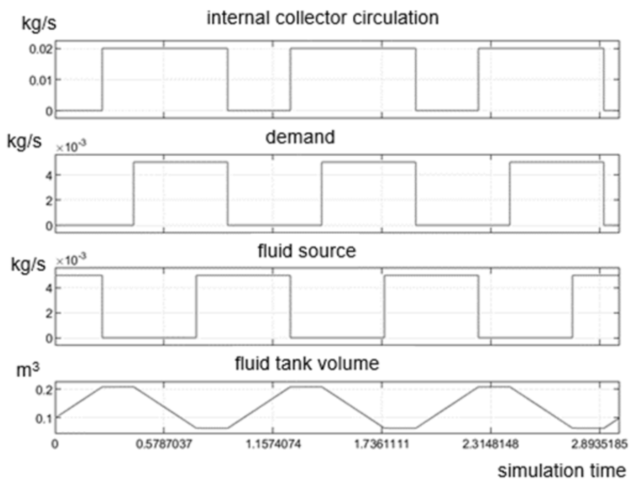

Fig. 6. Waveforms of the mass stream of the water medium flow in the collector's internal circuit, for a given demand and within the liquid source

The circulation pump operates during the sunshine hours to ensure maximum energy yield and limit the losses. The demand assumes water consumption from 10:00 to 22:00. The water supply described as "*fluid source*" assumes that the tank is replenished at night in order to limit the cooling of the stored water. During this time, an increase of the liquid volume in the tank is visible.

The values of irradiance adopted in the simulation come from own measurements database. Measurements were carried out using measuring station located on the roof of the Faculty of Automation, Robotics and Electrical Engineering building (Poznań University of Technology). Measurements are carried out using LB-900 pyranometers. Figure 7 shows the view of the measuring station.

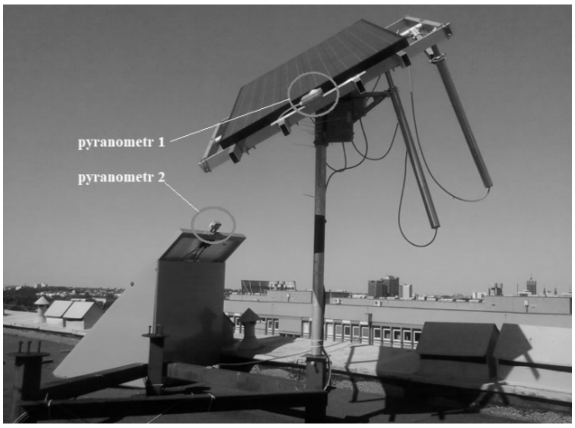

Fig. 7. View of the irradiance measuring station

Figure 8 shows an example of irradiance variability for one selected day of the year.

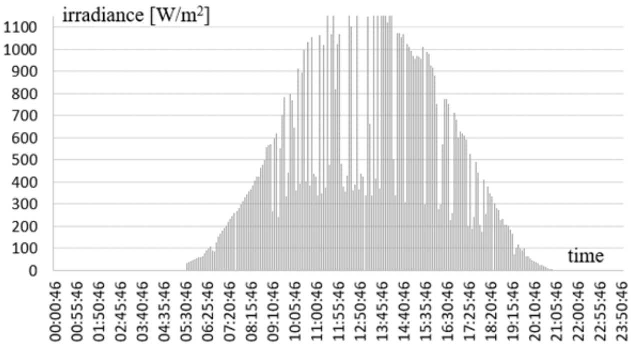

Fig. 8. Results of irradiance registration for July 17, 2014

The "*optical model*" block (Fig.5) allows to model the reflection, absorption and transmission of solar radiation in the glazing of the collector. The function of this block has two input signals (irradiance and angle of incidence). The output parameters are the value of irradiance recorded in the plane of the solar cells, after passing through the glazing of the collector. In addition, the information is provided about the heat absorbed by the glass and the heat flux reaching the solar cells. From the optical point of view, the collector pane consists of two parallel media boundaries in the form of air-to-glass and glass-to-air. Light is reflected and refracted at both these boundaries. The law of reflection and refraction describe the angles of a reflected and refracted radiation. The division of radiation energy between reflected and refracted rays is described by the Fresnel equations.

The values of reflection, absorption and transmission coefficients were determined on the basis of [20]. Figure 9 shows the dependence graphs of the optical coefficients used in the simulation on the angle of incidence of solar radiation.

Solar cells are the electrical structure of the collector. A single cell was modeled as a parallel connection of a current source, diode, shunt and series resistance. The cell has two inputs in the form of irradiance and temperature. In the collector model, a single-diode solar cell model was used. Figure 10 shows the current-voltage characteristics of the photovoltaic module used in the construction of the PV/T collector model.

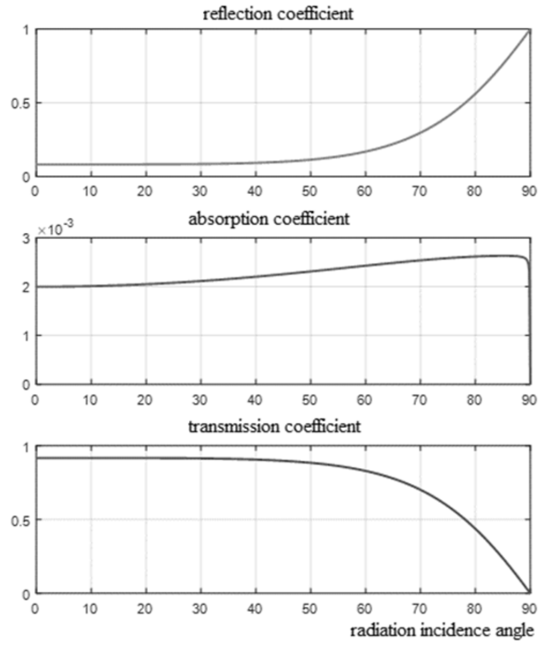

Fig. 9. Optical coefficients implemented in PV/T model

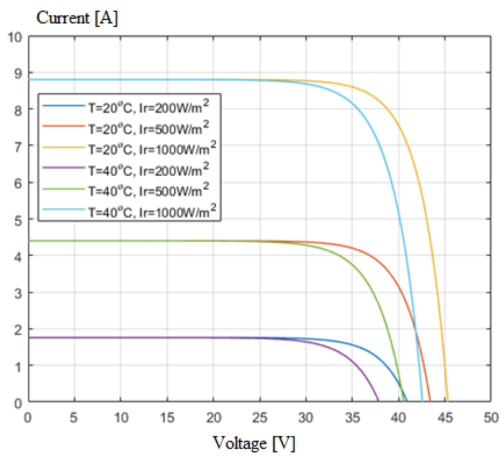

Fig. 10. Current-voltage characteristics of the photovoltaic module used in the PV/T collector model

The "*load*" block simulates the collection of electricity generated by the PV module and consists of a resistor, ammeter and voltmeter.

The thermal part of the collector consists of blocks simulating heat exchange between its elements and between the collector and the environment.

The external environment is represented by the "*ambient temperature*" block and the "*color temperature of the sky*" block. The ambient temperature is a reference point in the simulation of a heat flow between the front side of the collector and air as well as between the back side and air. The color temperature of the sky allows to determine heat transfer by radiation. It is a reference point in the calculation of heat losses from the collector glass. The temperature in the collector components is modeled by thermal mass type blocks available in the Matlab/Simulink. The temperature of the collector's glazing is represented by the "*glass*" block, while the temperature of the casing by the "*back cover*" block. For both blocks, the mass of the element and the material specific heat are determined. The exchanger temperature is represented by the "*exchanger*" block. The temperature at this point is the temperature on the outer wall of the pipeline where the heated water is located. The temperature in this place is measured in the "*temp sensor*" subsystem. Heat exchange between the components of the model is carried out by convection, radiation and conduction blocks.

The heat sources in the model are two subsystems "*heat on the glass*" and "*heat on PV*", grouped in the subsystem "*heat on collector*". Both subsystems retrieve information from the optical model.

The reference thermal power of the collector, for an irradiance of 1000 W/m^2 and at a temperature of 25ºC, is 450 W.

In the "*water circulation*" subsystem, heat collection from the collector exchanger is modeled. Figure 11 shows the structure of the water circulation subsystem.

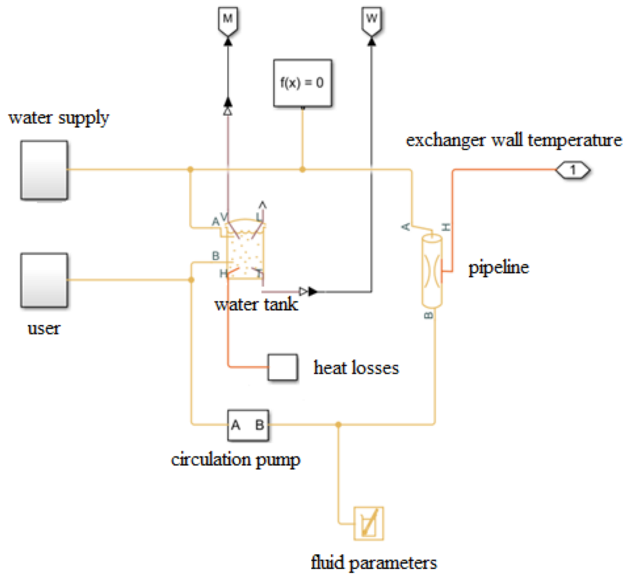

Fig. 11. Water circulation subsystem in the installation with a PV/T collector

To the "*pipeline*" block, from the thermal part of the model, a signal about the temperature of the exchanger wall and the water mass flow is transmitted.

The "circulation pump" subsystem models the water flow in the installation.

The circulating water is collected in a tank. The tank in the simulation has a volume of 250 l. The water heated in the exchanger and the water at the ambient temperature, which ensures the appropriate volume of the accumulated medium, flow into the tank. The outgoing water moves through the circulation pump to the exchanger or is collected by the user. Some part of the thermal energy accumulated in the tank is lost and these losses are implemented in the "*heat losses*" subsystem. The "*water supply*" subsystem ensures the replenishment of water in the system. Modeling the water intake by the user allows to determine the obtained thermal energy and thermal efficiency.

Computer simulation results

Days with the maximum daily value of 1000 W/m^2, 800 W/m^2 and 400 W/m^2 were selected from the irradiance database. Those days were selected which were characterized by a similar maximum daily ambient temperature equal to 22ºC.

The duration of the simulation is three days. Figures 12-14 show generated electric power (*P*), temperature of the collector exchanger (*ET*), water temperature in the tank (*TT*), heat losses from the rear side of the collector (*CHL*) and from the side of the glazing (*GHL*) for the assumed irradiance (*I*).

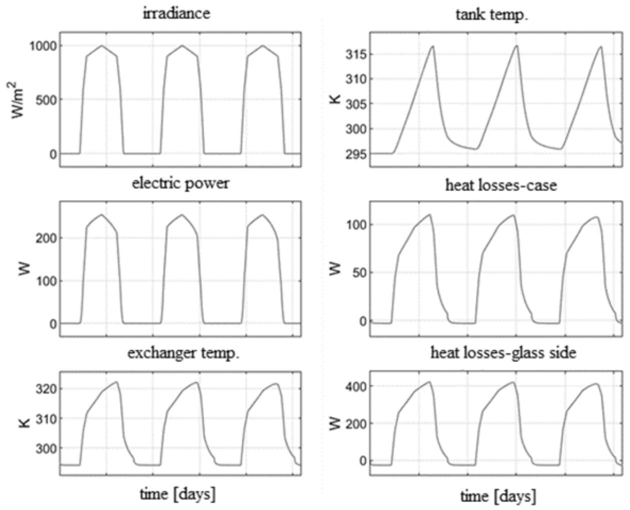

Fig. 12. Simulation results for days with a maximum daily irradiance equal to 1000 W/m^2

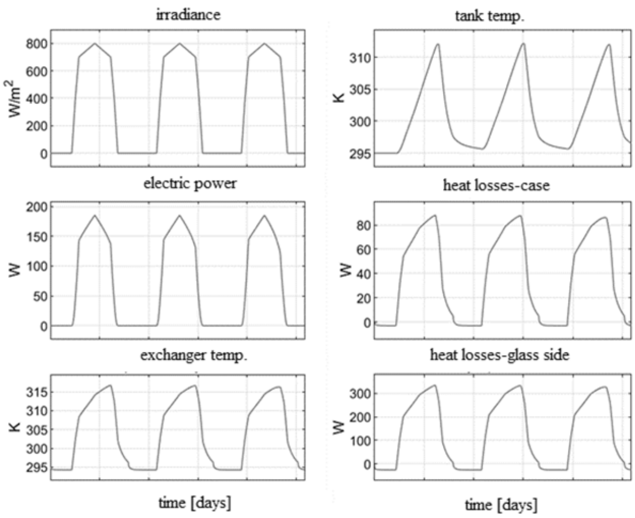

Fig. 13. Simulation results for days with a maximum daily irradiance equal to 800 W/m^2

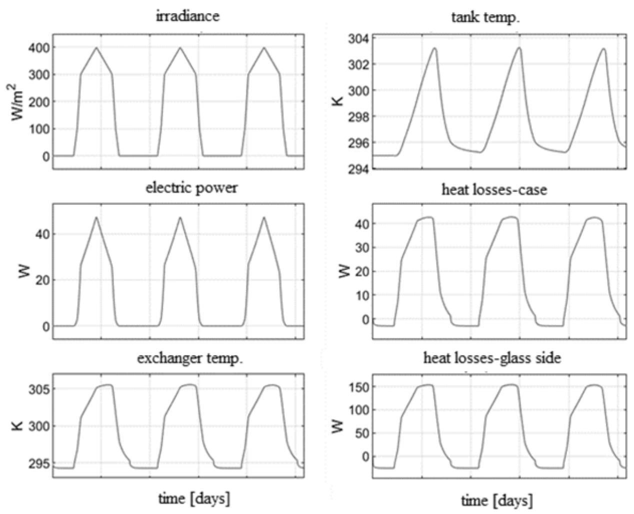

Fig. 14. Simulation results for days with a maximum daily irradiance equal to 400 W/m^2

The simulation results in the form of maximum values of analyzed parameters for the assumed irradiance values are presented in table 1, and the efficiency values in table 2.

Table 1. Simulation results – PV/T collector parameters

I [W/m^2]	P [W]	ET [K]	TT [K]	CHL [W]	GHL [W]
1000	254	322	316	110	420
800	185	316	312	88	335
400	47	305	303	42	154

Table 2. Simulation results – PV/T collector efficiency

I [W/m^2]	electrical efficiency [%]	thermal efficiency [%]	total efficiency [%]
1000	18,13	24,62	42,75
800	14,67	23,07	37,74
400	6,9	22,37	29,27

The simulation was also carried out for a reduced air temperature equal to 15ºC while maintaining the distribution of solar radiation with the maximum daily irradiance value of 1000 W/m^2.

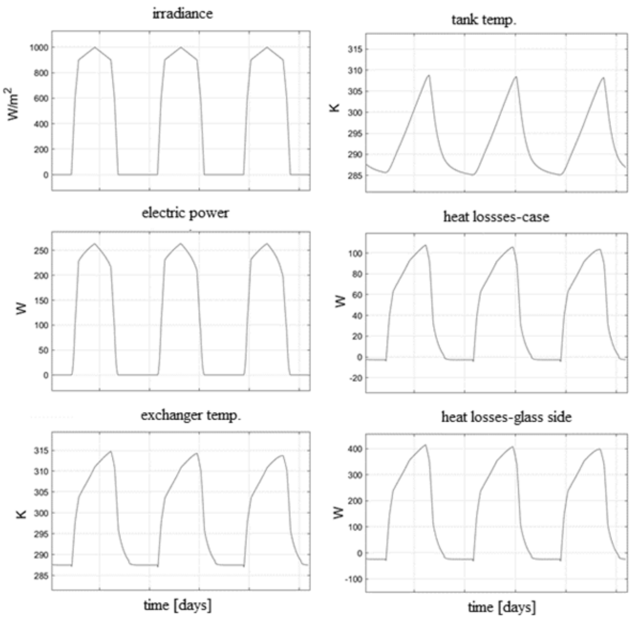

Fig. 15. Simulation results for days with a maximum daily irradiance value of 1000 W/m^2 and an ambient temperature of 15°C

Conclusions

Small scale PV/T collectors may be a promising solutions for maximal harvesting of the solar energy for residential prosumers.

An important external factor affecting the operating parameters of the hybrid collector is the solar radiation power density and the ambient temperature.

A significant variability of the system's operating parameters during the day is visible. The electrical power reaches the maximum value with the maximum value of irradiance. Exceeding 12:00 hour does not cause immediately a decrease in the tank and the collector :exchanger temperature value, which is only visible when the irradiance decreases further towards the evening hours.

When the irradiance values change to the level of 800 W/m^2 and 400 W/m^2, a decrease in the value of all tested parameters is noticeable.

Lower value of temporary insolation leads to slower heating of the collector as well as leads affect the decrease in electrical efficiency. The thermal efficiency of the modeled collector oscillates around 23%, regardless of the insolation in the analyzed period of time. The overall efficiency of the device decreases.

Heat losses depend on the temperature difference between the environment and the collector. For this reason, the points of the maximum losses coincide in time with the peak temperatures.

The efficiency of photovoltaic-thermal generators depends on the ambient air temperature. Its decrease results in an increase in electrical efficiency and electrical power. However, low ambient temperature has a negative effect on the obtained thermal energy. The maximum temperatures of the exchanger and water in the tank are reduced. The operation of PV/T collectors is therefore associated with a compromise between the electricity and heat generation. The temperature of the water in the tank depends on the temperature of the exchanger and is always lower. A large temperature difference intensifies losses and contributes to a significant reduction in the possibility of water medium heating.

Reducing the ambient temperature by 7ºC results in an increase in maximum electrical power by 9 W to 263 W. The maximum temperatures of the exchanger and water in the tank decreased, reaching respectively 314 K and 309 K from the initial values of 322 K and 316 K.

It should be noted that an important parameter for the effective operation of the PV/T collector is the operating mode and parameters of the used circulation pump. Its operation allows the collection of heat energy from the exchanger and storage in the tank. This aspect will be the subject of future simulation studies and laboratory tests using a real hybrid collector ASOL-375W$_p$/960W$_t$ with a regulation of the medium flow rate in the hydraulic part of the installation.

It should be emphasized that a significant part of the solar radiation spectrum, when using only photovoltaic modules, remains unused in the internal photovoltaic effect. The energy of solar radiation occurs in the form of heat loss. This heat can be recovered and used for domestic hot water or heating applications connecting solar cells with solar collector structures.

Some limitations of performed simulations and its results should be highlighted caused by the simplicity of the implemented PV/T collector model and the fact that some components are pre-defined in the Matlab/Simulink software. Regardless of this, the potential user of the photovoltaic-thermal solar collector may perform preliminary functional analyses, which may contribute to the verification of some design assumptions or even economic calculations.

***Autorzy**: dr inż. Artur Bugała, Politechnika Poznańska, Instytut Elektrotechniki i Elektroniki Przemysłowej, ul. Piotrowo 3a, 60-965 Poznań, E-mail: artur.bugala@put.poznan.pl; dr inż. Dorota Bugała, Politechnika Poznańska, Instytut Elektrotechniki i Elektroniki Przemysłowej, ul. Piotrowo 3a, 60-965 Poznań, E-mail: dorota.bugala@put.poznan.pl; mgr inż. Antoni Arendacz, Politechnika Poznańska, Instytut Elektrotechniki i Elektroniki Przemysłowej, ul. Piotrowo 3a, 60-965 Poznań, E-mail: antoni.arendacz@student.put.poznan.pl*

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