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doi:10.15199/48.2020.09.04

Analytical modelling of water sheet-and-tube Photovoltaic Thermal Collector

***Abstract**. This paper deals with analytical modelling of water sheet-and-tube photovoltaic thermal collector. The presented design will be integrated on PV modules of existing small photovoltaic system in Brestanica, Slovenia. Analysis of electrical and thermal performances for design of photovoltaic thermal module will be presented. The results show that the use of the installed water sheet-and-tube collector improves the electrical efficiency by 4%, while annually produce 1103 kWh of thermal energy with an average thermal efficiency of 68.86%. Furthermore, the cooling of photovoltaic system contributes to increasing the life time of photovoltaic system.*

Streszczenie.** Artykuł dotyczy modelowania analitycznego wodnego płytowo-rurowego fotowoltaicznego kolektora termicznego.. Prezentowany projekt zostanie zintegrowany z modułami fotowoltaicznymi istniejącego małego systemu fotowoltaicznego w Brestanicy w Słowenii. Przedstawiona zostanie analiza parametrów elektrycznych i cieplnych do projektowania fotowoltaicznego modułu termicznego. Wyniki pokazują, że zastosowanie zainstalowanego kolektora rurowo-rurowego poprawia sprawność elektryczną o 4%, a rocznie wytwarza 1103 kWh energii cieplnej przy średniej wydajności cieplnej 68,86%. Ponadto chłodzenie układu fotowoltaicznego przyczynia się do zwiększenia jego żywotności (**Modelowanie analityczne wodnego płytowo-rurowego fotowoltaicznego kolektora termicznego)

Keywords: sheet-and-tube, modelling, efficiency, temperature of PV modules, thermal energy
Słowa kluczowe: system płytowo-rurowy, modelowanie, temperatura modułu PV, energia cieplna

Introduction

A photovoltaic (PV) module converts the energy of light (solar energy) directly into electricity by the photovoltaic effect, whereby only a minor part of the solar energy is converted into electricity. A major part of the solar energy is converted into thermal energy, which results in an increase in the temperature of the PV module. Due to the negative temperature coefficient of the PV module, the electrical efficiency decreases with increasing temperature. Electrical efficiency can be increased by cooling the PV module, which is usually achieved by exposing the surface of the PV module to a cooling media (usually water or air), which absorbs the waste heat of the PV module via heat exchanger, and thus decreasing the temperature of the PV module. The obtained waste heat can be used in low-temperature heating systems.

Generally cooling techniques are divided into active and passive cooling techniques [1,2]. Active cooling techniques are based on systems for heat extraction utilizing active devices (pumps, funs, etc.) which needs to be powered by electricity. However, the passive cooling techniques refer to systems for heat extraction without additional power consumption and are based only on methods utilizing laws of thermodynamics (natural convection, thermosiphon effect, chimney effect, etc.). The integrated cooling system can increase the electrical efficiency up to 20% [3,4]. Grubišić et al. [2] analyzed and compared different cooling techniques and concluded that the most effective technique that produce additional power is active water cooling system. The PV module in combination with cooling system is called hybrid photovoltaic thermal collector/module (PVT). Active hybrid PVT collectors/modules are most commonly divided on concentrated [5-7] and flat-plate PVT modules. Flat-plate PVT modules/collectors can also be divided based on the cooling media, with water [8-12] and air [13-15] being the most commonly used media. Water has a higher thermal conductivity, heat transfer rate and heat carrying capacity than air, and thus provides more uniform cooling of the PV module [16]. Recent studies use nanoparticles for even more efficient cooling, as their thermal properties are even better than water [17,18].

Several works deal with different designs of sheet-and-tube collectors [19-21]. Ibrahim et al. [19] compare seven different sheet-and-tube designs to determine the best absorber design that gives the highest total efficiency. Authors in [20,21] present the correlation of sheet-and-tube material with energy gain and efficiency, while [22-25] present different analytical model for analysis of electrical and thermal performances of PVT systems.

Fig.1. Photovoltaic system installed near thermal power plant Brestanica, Slovenia.

This paper deals with analytical modelling of the PVT module and present the design of sheet-and-tube collector for PV module, that will be installed on existing small photovoltaic system (81.78 kWp) in Brestanica, Slovenia. The required measuring data was acquired from meteorological station that is installed near the PV system and measures the following data in the period of six years: intensity of solar radiation G, ambient temperature T_{amb}, temperature of the PV modules T_m and wind speed. Based on the measuring data the analysis of electrical, thermal and total power and efficiency were estimated for one particular day of the year and for each month of the year. Design of heat exchanger for PVT module presented in this paper were made for photovoltaic power plant installed in Brestanica, Slovenia. This photovoltaic system consists of a fixed field of PV modules oriented to the east tilted at 5°, as shown in Fig. 1. The PV modules perform function of the carport roof and the function of the photovoltaic system at the same time. Grid-connected PV system, consists of 282 mc-Si PV modules, with the maximum peak power of 290 Wp (per PV module), which gives a total installed power of

81.78 kWp. The field of PV modules is connected on six three-phase inverters (SMA11000) and on three single-phase inverters (SMA5000).

Methodology

Thermal conditions in PVT module can be described by the mathematical model of the flat-plate PVT collector [22-25]. The useful heat gain of a flat-plate thermal collector is described by (1):

$$Q_u = mc_p\left(T_{fo} - T_{fi}\right) \quad (1)$$

where m is the mass flow rate of cooling media, C_p is the specific heat of cooling media, T_{fo} is the fluid outlet temperature and T_{fi} is the fluid inlet temperature. Thermal efficiency of a flat-plate thermal collector is given by (2):

$$\eta_{th} = \frac{Q_u}{GA_c} \quad (2)$$

where G is the intensity of solar radiation and A_c is the area of the PVT module. Equation (1) can be rewritten in terms of the absorber plate temperature by (3):

$$Q_u = A_c\left[S - U_L\left(T_{ap} - T_{amb}\right)\right] \quad (3)$$

where S is the absorbed solar energy, U_L is the overall heat loss coefficient, T_{ap} is the absorber plate temperature and T_{amb} is the ambient temperature. Authors in [25] simplified (3) since it includes difficulties to calculate (4):

$$Q_u = A_c F_r\left[G(\tau\alpha) - U_L\left(T_{fi} - T_{amb}\right)\right] \quad (4)$$

where τ is the transmittance and α is the absorbance of the glass cover, F_r is the heat removal factor of the PVT module and is described by (5):

$$F_r = \frac{mc_p}{A_c U_L}\left\{1 - \exp\left(-\frac{A_c U_L F_e}{mc_p}\right)\right\} \quad (5)$$

where F_e is the collector efficiency factor and is described by (6):

$$F_e = \frac{\frac{1}{U_L}}{W\left[\frac{1}{U_L}\left[D_o + \left(W - D_o\right)F_{fe}\right] + \frac{1}{\lambda_b} + \frac{1}{\pi D_i h_{fi}}\right]} \quad (6)$$

where W is the tube spacing, D_o is the outside tube diameter, D_i is the inside tube diameter, λ_b is the thermal conductivity of the bond between the fin and tube, h_{fi} is the heat transfer coefficient of cooling media and F_{fe} is the fin efficiency factor, respectively. The fin efficiency factor is described by (7):

$$F_{fe} = \frac{\tanh(x)}{x} \quad (7)$$

where x is the fin thickness described by (8):

$$x = \sqrt{\frac{U_L}{\lambda_{ap}\delta_{ap}}}\left(\frac{W - D_o}{2}\right) \quad (8)$$

where δ_{ap} is the thickness and λ_{ap} is the thermal conductivity of sheet-and-tube collector. Cross section of sheet-and-tube water collector that is mounted on the backside of the PVT module is illustrated in Fig. 2.

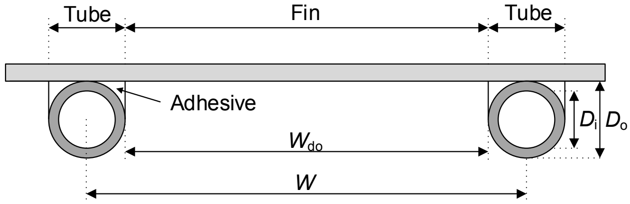

Fig.2. Cross section of sheet-and-tube water collector

The overall heat loss coefficient U_L of the collector can be written as (9) and is the sum of the bottom U_b (10), side U_s (11) and, top U_t, (12) loss coefficients:

$$U_L = U_b + U_s + U_t \quad (9)$$

$$U_b = \frac{\lambda_{lb}}{\delta_{lb}} \quad (10)$$

where δ_{lb} is the thickness and λ_{lb} is the thermal conductivity of the collector bottom insulation.

$$U_s = \frac{2L_3\left(L_1 + L_2\right)\lambda_{ls}}{L_1 L_2 \delta_{ls}} \quad (11)$$

where L_1, L_2, L_3 are the length, width and height of PVT module, δ_{ls} is the thickness and λ_{ls} is the thermal conductivity of collector side insulation.

$$U_t = \left[\left\{\frac{N}{\frac{C}{T_{ap}}\left[\frac{T_{ap} - T_{amb}}{N + f}\right]^e} + \frac{1}{h_w}\right\}^{-1} + \frac{\sigma\left(T_{ap} + T_{amb}\right)\left(T_{ap}^{\;2} + T_{amb}^{\;2}\right)}{\left(\varepsilon_p + 0{,}00591Nh_w\right)^{-1} + \frac{2N + f - 1 + 0{,}133\varepsilon_p}{\varepsilon_g} - N}\right] \quad (12)$$

where N is the number of glass covers, σ is the Stefan-Boltzmann constant, ε_p is the emissivity of plate, ε_g is the emissivity of glass and h_w is the heat transfer coefficient of wind. Coefficient h_w, C, f in *e are* the empiric coefficients defined by (13) – (16):

$$h_w = 5{,}7 + 3{,}8v_w \quad (13)$$

$$C = 520\left(1 - 0{,}000051\beta^2\right) \quad (14)$$

$$f = \left(1 + 0{,}089h_w - 0{,}1166h_w\varepsilon_p\right)\left(1 + 0{,}07866N\right) \quad (15)$$

$$e = 0{,}43\left(1 - \frac{100}{T_{ap}}\right) \quad (16)$$

where v_w is the wind speed and $ß$ is the inclination angle of the PVT module.

The most important electrical performance parameters of the PVT module are undoubtedly electrical efficiency and power. The electrical efficiency of the PV module, which is a function of module temperature, is defined by (17).

$$\eta_{el} = \eta_r\left(1 - \gamma\left(T_m - T_r\right)\right) \quad (17)$$

where η_r is the reference efficiency of the PV module, γ is the temperature coefficient, T_m is the temperature of the PV module and T_r is the reference temperature. Electrical power of the PVT module is given by (18):

(18) $$P_{el} = \frac{\eta_{el} G A_C}{100}$$

Total efficiency is given by (2) and (17), and can be written as (19):

(19) $$\eta_C = \eta_{el} - \eta_{th}$$

Design of sheet-and-tube water collector

The sheet and tube collector is designed as direct flow absorber and could be later easily mounted to the back side of the existing PV modules of the photovoltaic system (see Fig. 2). Designed sheet-and-tube collector, shown in Fig. 3 is made of copper tubes with an outer diameter of 13,4 mm and an inner diameter of 12,4 mm. Sheet-and-tube collector consist of two tubes for inlet and outlet of the cooling media and nine parallel tubes that reduce the temperature of cells along the PV module with total length of 18,7 m. Main technical data of the designed sheet-and-tube collector is listed in Table 1.

Table 1. Technical data of sheet-and-tube collector

Parameter	Symbol	Value	Unit
Number of glass covers	*N*	0	/
Stefan-Boltzman constant	*σ*	5,056e-08	W/m^2K^4
Absorber plate emissivity	ε_p	0,95	/
Glass cover emissivity	ε_g	0,88	/
TE module inclination	*ß*	5	°
Wind speed	v_{wind}	2	m/s
Convection heat transfer coefficient of wind	h_w	9,5	W/m^2K
Glass cover absorption coefficient	*α*	0,95	/
Glass cover transmittance	*τ*	0,88	/
Length of TE module	*L1*	1,98	m
Width of TE module	*L2*	0,88	m
Height of TE module	*L3*	0,05	m
Side insolation thickness	δ_{Is}	0.01	m
Bottom insolation thickness	δ_{Ib}	0,02	m
Insolation thermal conductivity	$\lambda_{Is}=\lambda_{Ib}$	0,045	W/mK
Distance between tubes	*W*	0,0964	m
Tube outer diameter	D_o	0,0134	m
Tube inner diameter	D_i	0,0124	m
Bond thermal conductivity	λ_b	237	W/mK
Convection heat transfer coefficient of water	h_{fi}	1000	W/m^2K
Absorber plate thickness	δ_{ap}	0,00005	m
Absorber plate thermal conductivity	λ_{ap}	0,1583	W/mK
Water mass flow rate	*m*	0,004	kg/s
Water specific heat	C_p	4200	J/kgK
Absorber plate area	A_c	1,75	m^2
Number of TE module	N_{TE}	282	/
PV cell reference temperature	T_r	25	°C
PV cell reference efficiency	η_r	0,15	/
PV cell temperature coefficient	*γ*	0,0048	1/°C

Results

On the basis of presented analytical model and water sheet-and tube design of the PVT module, the analysis of electrical and thermal performances was estimated for one particular day of the year and for each month of the year. Fig. 4 shows electrical, thermal and maximum power of the PVT system.

Fig.3. Sheet-and-tube collector mounted on the backside of the PV module.

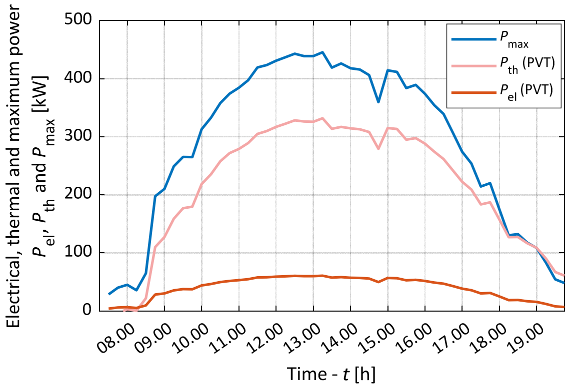

Fig.4. Electrical, thermal and maximum power of the PVT system.

Additional thermal power of 328,32 kW with efficiency of 74,09% was obtained from PVT system as a result of absorbing heat from module at cooling water mass flow rate of 0.004 kg/s. The temperature of outlet water from heat exchanger was found at 37 °C. Fig. 5 shows electrical power of the PV and PVT system.

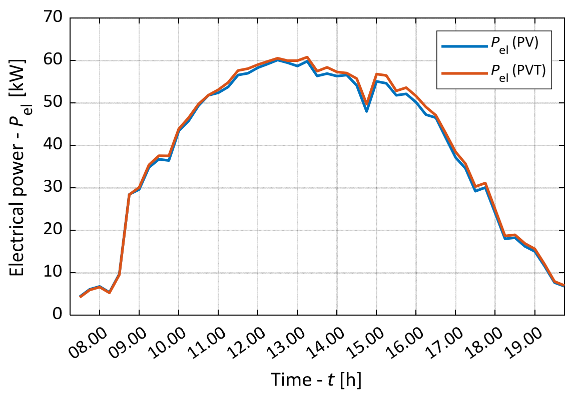

Fig.5. Electrical power of the PV and PVT system.

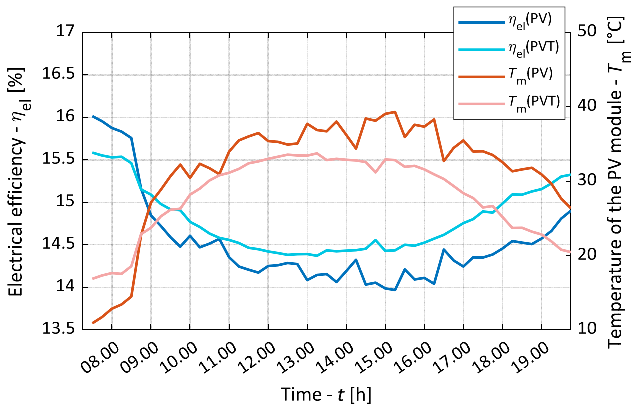

Fig.6. Electrical efficiency and PV / PVT module temperature.

As a result of cooling the PVT module the electrical power increased by 4% with the inlet water temperature in the sheet-and-tube collector being 17,5 °C. Fig. 6 shows the electrical efficiency and PV / PVT module temperature.

Fig. 6 shows that the electricity produced decreases with increasing temperature of the PV / PVT module. The cooling of PV / PVT modules is more efficient in the afternoon hours, when the ambient temperatures are much higher compared to the noon hours at the same intensity of solar radiation. Fig. 7 shows the electrical, thermal and total efficiency of PVT system at water mass flow rate of 0.004 kg/s.

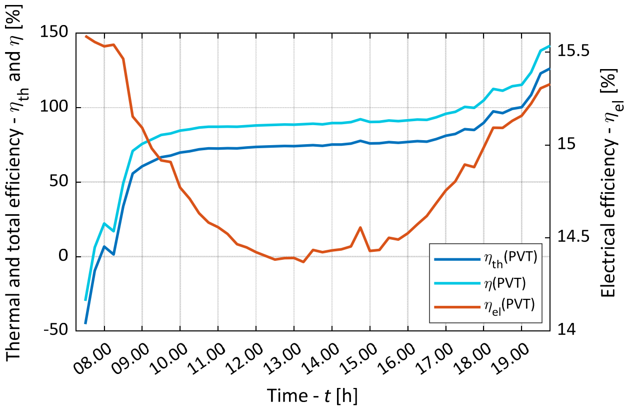

Fig.7. Electrical, thermal and total efficiency of the PVT system.

It can be seen from Fig. 7 that the highest electrical efficiency is achieved at noon hours when the temperature of the ambient is lower than in the afternoon, while in case of thermal and total efficiency is exactly the opposite.

As mentioned in the introduction, the excess heat from the PVT system can be used in various heat applications. In the case presented in the paper, the PV system is located next to the thermal power plant and excess heat can be removed through the cooling tower of the thermal power plant. The low water temperature in the cooling tower (see Table 2. - T_{fi}) represents ideal conditions for heat removal from PVT system, with 2330 m^3 of water. On the basis of data presented in Table 2 regarding water temperature in cooling tower T_{fi}, intensity of solar irradiation G, ambient temperature T_{amb} and temperature of PV module T_m measured in the six-year period (average value), the annual electrical, thermal and total power and efficiency was calculated for classical PV and cooled PVT system. The results of electrical, thermal and total power and efficiency are shown in Fig. 8 and 9.

Table 2. Measured data over a six-year period.

Month	***G*** [W/m^2]	T_{amb} [°C]	T_m [°C]	T_{fi} [°C]
Jan	126	4,49	6,58	4
Feb	164	5,08	7,91	4,2
Mar	280	11,43	15,73	4,7
Apr	299	15,85	23,10	5
May	344	21,09	29,75	10
Jun	353	24,14	34,25	13,5
Jul	395	27,46	37,72	17,5
Aug	398	26,96	37,13	16,5
Sep	289	19,58	26,56	13,5
Oct	204	13,88	18,06	10
Nov	130	9,20	10,86	6
Dec	125	4,16	5,60	5

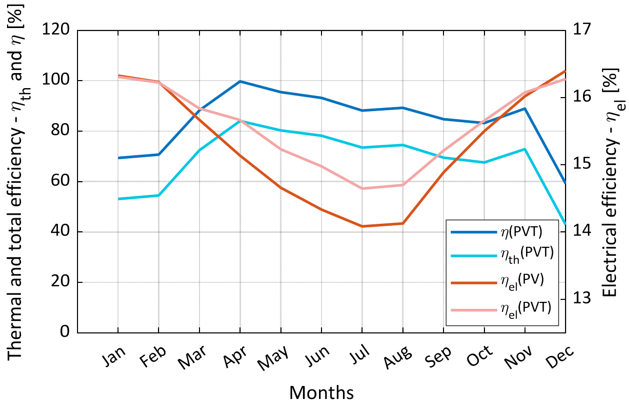

Fig.8. Electrical, thermal and total efficiency of the PVT system.

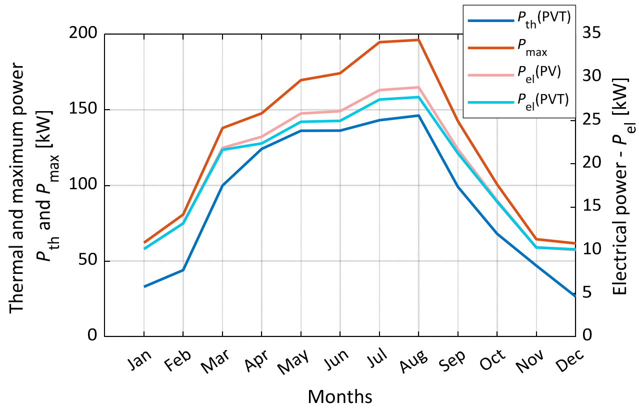

Fig.9. Electrical, thermal and maximum power of the PVT system.

Fig. 8 and 9. shows that the electrical efficiency increases by 4,49 %, as well as the electrical power. The PVT system produces 1103 kWh of annual thermal energy with an average thermal efficiency of 68,81 %.

Conclusion

This paper deals with analytical modelling of water sheet-and-tube PVT collector. The main objective of this paper is to present the design of the sheet-and-tube PVT collector that will be mounted on the backside of the existing PV system. The results show that using the presented design of water sheet-and-tube collector, the temperature of the PV module is reduced, which consequently increases the efficiency and energy production by 4%. In addition, the 1103 kWh of thermal energy is obtained per year, which can be used in various thermal applications for heating. The future work of this study will be the installation of the presented design of water sheet-and-tube collectors on the existing PV system and thus validating the model results with the measurements.

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