Theoretical Analysis of Solar Unglazed Hybrid Photovoltaic-Thermal Liquid Collector

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Abstract

Detailed mathematical model of unglazed solar flat-plate hybrid photovoltaic-thermal (PV-T) liquid collector has been presented for standalone and building envelope integrated alternative. Model calculates the heat transfer from absorber (PV cell) to ambient and heat transfer from absorber to liquid through fin-pipe cooler. Influence of design parameters and operation conditions (temperature, wind, solar irradiance) on electrical and thermal characteristics of PV-T collector has been analyzed in several examples and results have been presented. Performance modelling possibilities of the model for unglazed PV-T or separate PV and PT solar collectors have been shown.

1. Introduction

Utilization of solar energy being a scarce energy source needs large area of south-facing collecting surfaces. Rational use of building envelopes for collection of the solar energy and its conversion to required energy carrier results into integration of active solar devices into the building envelope structures and leads to multi-functional or hybrid solar collector configurations combining several purposes (heat and electricity generation, daylighting, air-liquid) in a single unit [1]. Building integrated solar hybrid flat-plate PV-T collector represents an advanced multifunctional configuration of solar device, which provides combined heat and power production (solar cogeneration). Such a combination can result in overall energy production higher than for standard separate PV and PT devices at the same installed area. Paper concentrates on mathematical modelling of unglazed solar flat-plate PV-T liquid collector. Influence of construction design and operation parameters of PV-T collector on its electric and thermal characteristics has been shown at examples.

2. Solar hybrid PV-T collectors

Today, standard commercial PV modules cannot convert more than 15 % of incident solar radiation to electricity, rest of energy is converted to waste heat which is partly transferred to ambient and partly heats the PV module and increases its temperature. Increase of PV cell temperature affects the efficiency of photovoltaic solar to electricity conversion negatively. Decrease of PV cell electrical efficiency η_{el} with temperature t can be expressed by simplified linear function

$$\eta_{\mathrm{el}} = \eta_{\mathrm{el,r}}\left[1-\beta\left(t-t_{\mathrm{r}}\right)\right] \tag{1}$$

where $\eta_{\mathrm{el,r}}$ is PV cell electric efficiency at reference conditions, t_{r} is reference temperature of PV cell and β is temperature coefficient. Table 1 shows typical ranges of temperature coefficient for different types of PV cells. To assure high electric efficiency, it is desirable to cool PV modules and to use the waste low-temperature heat in a reasonable way.

Table 1. Typical values of temperature coefficient for different types of PV cells.

PV cell type	β **[%/K]**
Crystalline Si	0,35 to 0,52
Amorphous Si	0,10 to 0,30
CIS	0,33 to 0,60
CdTe	0,18 to 0,36

In the case of architectonically and aesthetically preferred building integrated installations (BIPV), much higher temperature of PV cells appears compared to standalone modules favourably exposed to wind effects. BIPV modules suffer by high thermal loads originated from limited cooling by ambient air due to presence of insulation layer at backside and due to reduced wind induced heat losses for envelope integrated surfaces. Extreme thermal load in summer sunny but windless day can result in PV temperatures up to 100 °C for building envelope integrated modules and cause degradation or even destruction of PV cells.

Introduction of active PV cooling results in hybrid photovoltaic-thermal collectors (PV-T collectors) which can provide low-temperature heat and electricity, while heat production is several times higher than electricity. Through the solar electricity and heat cogeneration, the total energy output per unit collector area is higher than the outputs of standard PV module and thermal collector placed and operated separately with the equal total area. Hybrid PV-T collectors can be realised in several principal alternatives: glazed or unglazed, flat-plate or concentrating and with different heat removal fluids (air, liquid) [2, 3].

Hybrid PV-T air collectors with natural cooling don’t allow effective removal of the heat from PV cell. On other hand forced air circulation consumes auxiliary electricity which can generally negate the purpose of cooling (higher electricity gain). Limited potential for building integration due to large air duct systems and low usability of ambient warm air for cooling in summer season can be brought in as additional disadvantages of hybrid PV-T air collectors concept.

Contrary to PV collectors cooled by air, hybrid PV-T liquid collector concept seems to be more suitable for BIPV applications if combined with efficient use of low temperature heat, e.g. for cold water preheating, swimming pool heating circuits or primary circuits of heat pumps.

3. Mathematical model

A detailed mathematical model of unglazed solar flat-plate hybrid PV-T liquid collector (PVT-NEZ) has been evolved based on theory for energy balance of solar thermal collectors [4] expanded for photovoltaic conversion [5]. Input parameters of the model are thermal, optical, electrical and geometrical properties of individual parts of PV-T collector (e.g. PV cell: reference electric efficiency $\eta_{el,r}$, temperature coefficient β; absorber-cooler: material conductivity, geometry of the bond, spacing of risers W), climate conditions (solar irradiance G, ambient temperature t_a, wind velocity w) and operation conditions (temperature of fluid entering collector t_{c1}, mass flow rate $\dot{m}$). Output parameters of the model are usable electric power $\dot{Q}_{el}$ and thermal power $\dot{Q}_{th}$ together with respective efficiencies and temperature of the fluid leaving the PV-T collector t_{c2}.

Mathematical model PVT-NEZ consists of both external energy balance of PV-T absorber (heat transfer from PV-T absorber surface to ambient) and internal energy balance of PV-T absorber (electric yield, heat transfer from PV-T absorber surface to liquid), see Fig. 1.

3.1. External energy balance of the absorber

Heat flows from PV-T absorber surface to ambient by radiation, wind convection and envelope conduction for building integrated alternative are calculated within an iterative loop and temperature dependent overall U-value of PV-T collector is determined.

Sky radiation heat transfer coefficient $h_{r,sky}$ is calculated from equation by Swinbank [6], backside radiation-to-roof heat transfer coefficient $h_{r,roof}$ is calculated from emissivities of respective surfaces. Wind convection heat transfer coefficient h_w is determined from McAdams correlation [7]. Overall heat loss coefficient for standalone alternative is given by

$$U = \left(h_{r,sky} + h_{w,front}\right) + \left(h_{r,roof} + h_{w,back}\right) \tag{2}$$

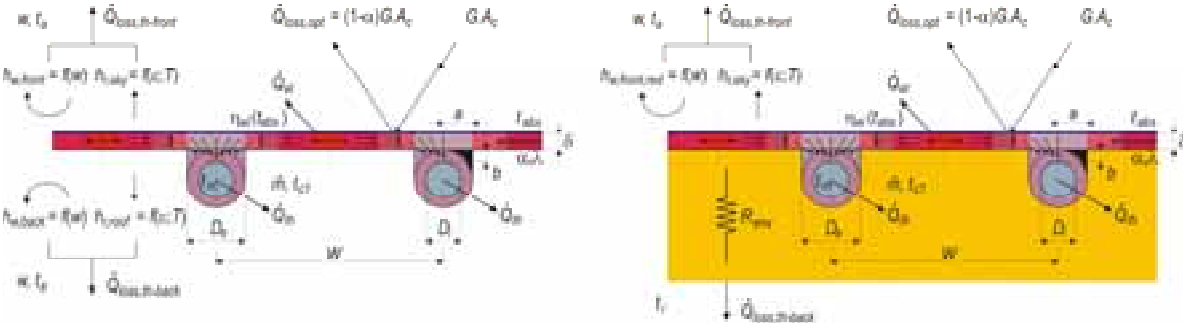

Fig. 1. Scheme of unglazed hybrid PV-T liquid collector model (standalone, building envelope integrated).

Model for building integrated PV-T collector considers envelope thermal resistance R_{env} at the back side of the absorber surface.

$$U = \left(h_{r,sky} + h_{w,front,red}\right) + \frac{1}{R_{env}} \tag{3}$$

Wind convection coefficient at front surface of building envelope integrated absorber is reduced in accordance with Sparrow‘s simplified approach [8].

In line with Florschuetz [5], the value of heat loss coefficient modified with a term expressing the solar radiation flow extracted as an electric power by PV cell is determined as

$$\widetilde{U} = U - G\eta_{el,r}\beta \tag{4}$$

3.2. Internal energy balance of the absorber

Heat flow from PV-T absorber surface to heat transfer liquid is calculated with theoretical approach modified by Florschuetz [5] with use of iteration cycle. Modified efficiency factor for hybrid PV-T collector is given by equation

$$\tilde{F}' = \frac{1/\tilde{U}}{W\left[\dfrac{1}{\tilde{U}[2a+(W-2a)F]} + \dfrac{1}{C_{\mathrm{bond}}} + \dfrac{1}{h_{\mathrm{i}}\,\pi\,D_{\mathrm{i}}}\right]} \tag{5}$$

where F is fin efficiency, W [m] is spacing of risers, a [m] is size of the bond, C_{bond} [W/mK] is bond conductance and D_{i} [m] is internal diameter of riser. Internal forced convection heat transfer coefficient h_{i} is calculated according to Shah [9].

Modified heat removal factor of hybrid PV-T collector is given by equation

$$\tilde{F}_{\mathrm{R}} = \frac{\dot{m}c}{A_{\mathrm{c}}\tilde{U}}\left[1-\exp\left(-\frac{A_{\mathrm{c}}\tilde{U}\tilde{F}'}{\dot{m}c}\right)\right] \tag{6}$$

where $\dot{m}$ [kg/s] is liquid mass flow rate, c [J/kgK] is specific thermal capacity of the liquid and A_{c} [m^2] is solar collector area.

Thermal power output of the hybrid PV-T collector is

$$\dot{Q}_{\mathrm{th}} = A_{\mathrm{c}}\tilde{F}_{\mathrm{R}}\left[\tilde{S} - \tilde{U}(t_{\mathrm{c1}} - t_{\mathrm{a}})\right] \tag{7}$$

where $\tilde{S}$ [W/m^2] is a part of solar radiant flux converted to heat given as

$$\tilde{S} = G\alpha\left(1 - \frac{\eta_{\mathrm{el,a}}}{\alpha}\right) \tag{8}$$

where α is absorptivity of PV cell and $\eta_{\mathrm{el,a}}$ is electric efficiency of PV cell at ambient temperature t_{a}.

Electric power output of the hybrid PV-T collector is

$$\dot{Q}_{\mathrm{el}} = A_{\mathrm{c}}G\eta_{\mathrm{el,a}}\left\{1 - \frac{\eta_{\mathrm{el,r}}\beta}{\eta_{\mathrm{el,a}}}\left[\tilde{F}_{\mathrm{R}}(t_{\mathrm{c1}} - t_{\mathrm{a}}) + \frac{\tilde{S}}{\tilde{U}}(1 - \tilde{F}_{\mathrm{R}})\right]\right\} \tag{9}$$

Mean absorber surface temperature t_{abs} (PV cell temperature) and mean liquid temperature t_{m} can be determined from temperature of liquid entering into collector t_{c1} from equations

$$t_{\mathrm{abs}} = t_{\mathrm{c1}} + \frac{\dot{Q}_{\mathrm{th}}/A_{\mathrm{c}}}{\tilde{F}_{\mathrm{R}}\tilde{U}}(1 - \tilde{F}_{\mathrm{R}}) \tag{10}$$

$$t_{\mathrm{m}} = t_{\mathrm{c1}} + \frac{\dot{Q}_{\mathrm{th}}/A_{\mathrm{c}}}{\tilde{F}_{\mathrm{R}}\tilde{U}}\left(1 - \frac{\tilde{F}_{\mathrm{R}}}{\tilde{F}'}\right) \tag{11}$$

Both external and internal energy balances of absorber are mutually dependent and superior cycle transfers the results of external balance to internal balance (collector heat loss coefficient U resp. $\widetilde{U}$) and results of internal balance to external balance (mean absorber temperature t_{abs}).

4. Characteristics of PV-T collector

Mathematical model PVT-NEZ of unglazed solar flat-plate PV-T liquid collector allows to analyze and to optimize the collector construction based on detailed design parameters and operation / climate conditions. Mathematical model is an universal tool, the electric and thermal output and efficiency can be evaluated for PV-T collector configuration as well as only thermal output for strictly unglazed thermal collector (efficiency $\eta_{el,r} = 0$) or strictly electric output of PV module (liquid mass flow = 0 kg/s) with temperature and solar irradiance effects.

Graphs in Fig. 2 and 3 show different types of characteristics for PV-T collector evaluated with use of mathematical model PVT-NEZ. The characteristics have been evaluated for operation / climate conditions and PV-T collector design parameters given in Table 2. Thermal resistance of building envelope R6 has been assumed in building integrated alternative.

Table 2. General conditions and design parameters for assessment of PV-T collector characteristics.

Climatic conditions	
solar irradiance	$G = 1000$ W/m^2
ambient temperature	$t_a = 25$ °C
wind velocity	$w = 0$ or 3 m/s
PV cell parameters	
temperature coefficient	$\beta = 0{,}45$ %/K
reference efficiency	$\eta_{el,r} = 12$ %
reference temperature	$t_r = 25$ °C
Absorber – cooler parameters	
liquid (water) mass flow rate	$\dot{m} = 0{,}02$ kg/s.m^2
risers distance	$W = 100$ mm
risers diameter	D_e / D_i = 10/8 mm
absorber-cooler thickness	$\delta = 0{,}3$ mm
absorber-cooler material	copper
bond heat conductance	$C_{bond} = 250$ W/m.K

Graphs in Fig. 2 show contradictory performance at climate conditions (wind velocity, ambient temperature) for PV-T collector in heat and electricity production regimes. Higher wind velocity (also lower ambient temperature) leads to higher electric efficiency but to lower thermal efficiency of unglazed PV-T collector due to higher heat loss. Similarly, the integration of PV-T collector into building envelope has increased the thermal efficiency and heat production, but at the expense of electric efficiency.

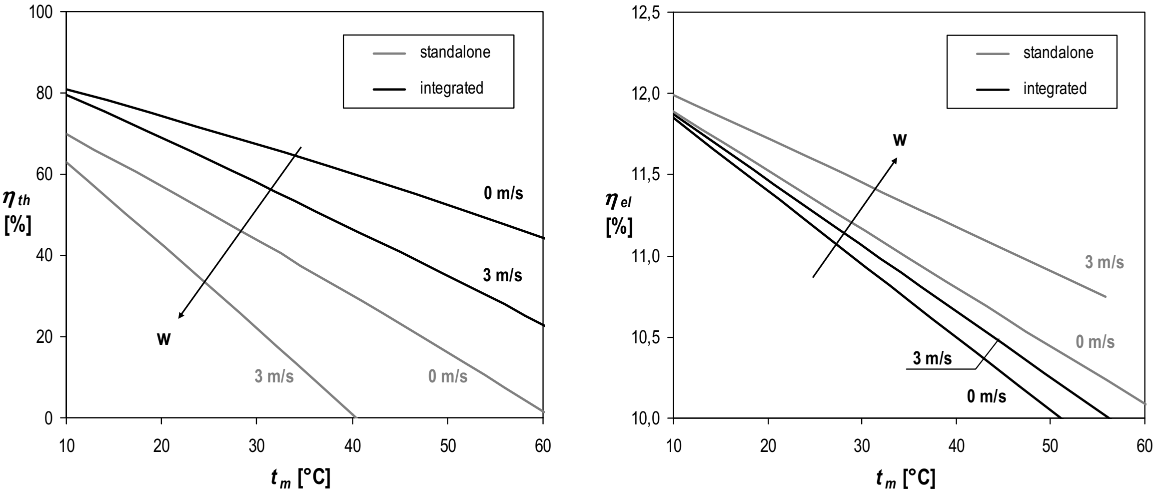

Fig. 2. Thermal and electric efficiency characteristics of PV-T collector.

Fig. 3 shows the electric efficiency characteristics of PV module without active cooling in standalone and building integrated alternative at different solar irradiance and wind velocity level (ambient temperature 25 °C). It is apparent that simple integration of PV modules into building envelope causes significant thermal stress for PV cells, temperatures of PV cells excess the maximum values (usually 85 °C) and can induce the degradation or even destruction of PV cells at extreme climate conditions.

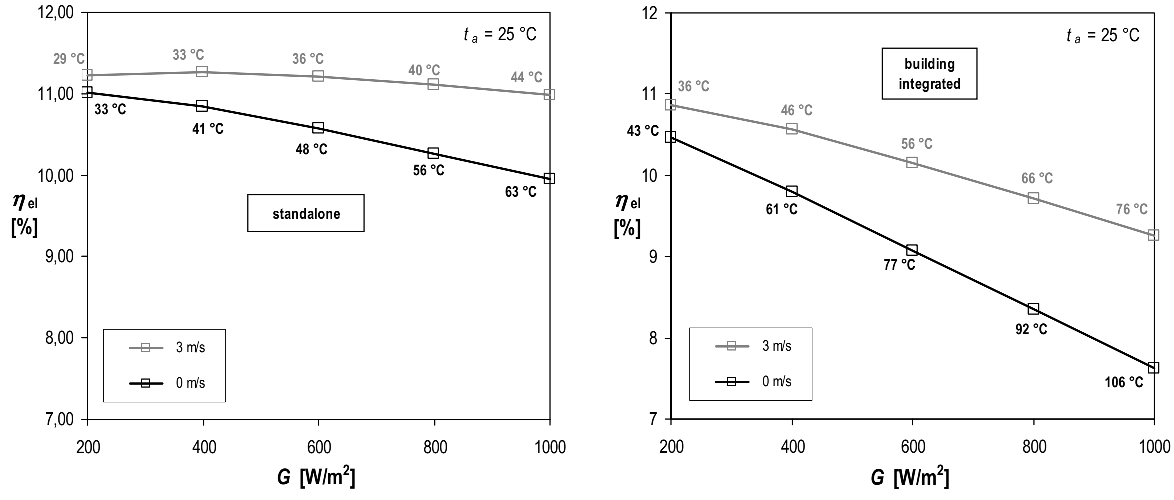

Fig. 3. Efficiency and temperature of PV modules without cooling (standalone, building envelope integrated).

5. Analysis of construction

Mathematical model PVT-NEZ allows to monitor the influence of variance in PV-T absorber-cooler design parameters on electric/thermal characteristics of hybrid PV-T collector and to optimize absorber-cooler construction. Further analyses follow only building envelope integrated PV-T collectors due to potentially more suitable application of liquid cooled hybrid collectors. Reference parameters of PV cells and absorber have been adopted from Table 2 except selected variable parameters in given examples. Extreme summer climate conditions (solar irradiance 1000 W/m^2, ambient temperature 25 °C, zero wind velocity) have been considered to emphasize the influence of analyzed design parameters.

5.1. Absorber-cooler risers distance

Spacing of absorber-cooler pipes (risers) defines the width of heat transfer fin, i.e. heat conduction path from surface (PV cells) which together with fin thermal conductivity and thickness determines heat resistance between PV cells and liquid cooled bond between absorber and riser (see Fig. 4). Graph in Fig. 4 (left) shows the influence of heat transfer fin width made of 0,3 mm thick copper on PV-T collector efficiency (thermal, electric) for given values 50 mm and 150 mm. Generally, smaller risers the spacing leads to better heat removal but higher density of risers and material use. Model allows to optimize the spacing to assure sufficient PV cells cooling with low material content.

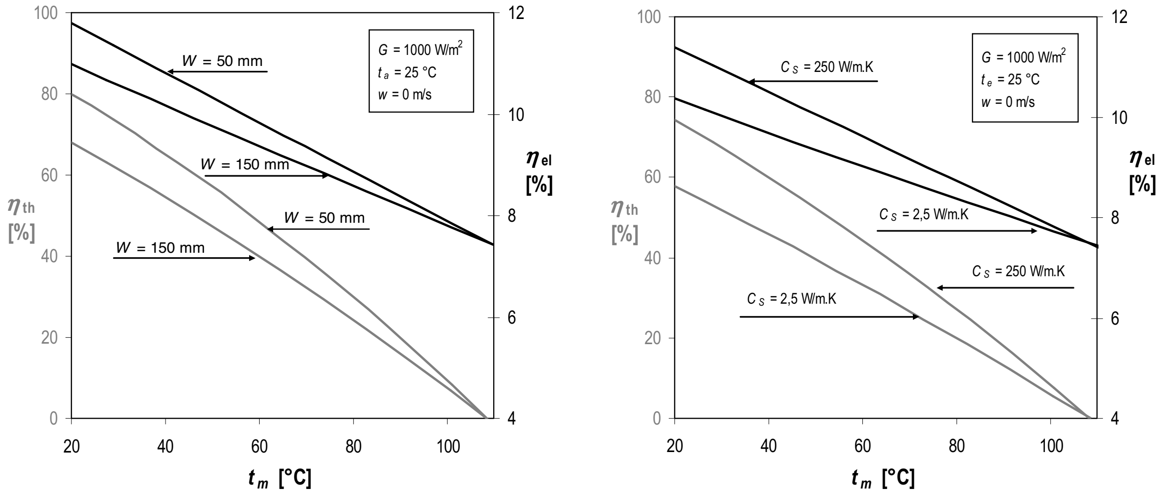

Fig. 4. Influence of risers spacing and absorber-pipe bond conductance on thermal and electric efficiency of flat-plate hybrid PV-T collector

5.3. Absorber-pipe thermal bond conductance

Thermal resistance between the heat conductive fin (absorber) and pipe with flowing liquid can play a considerable role in effectiveness of heat removal from PV cell. Similarly to solar flat-plate thermal collectors, sufficiently firm and conductive absorber-pipe bond with conductance above 100 W/m.K is important. Notable reduction of efficiency parameters results as far as from very low thermal quality of the bond, e.g. clamped fin on the pipe (point contact) or just attached pipe to fin with heat conductance in order of several W/m.K (see Fig. 4, right).

6. Conclusions

In order to analyze and optimize the unglazed solar flat-plate hybrid PV-T liquid collector in standalone and building envelope integrated alternatives, a detailed mathematical model with iterative calculation procedure of external and internal energy balance of PV-T absorber has been evolved.

Analysis of building envelope integrated PV modules has shown off the issue of high operation temperatures (up to 100 °C) inducing the thermal stresses negatively affecting their life time. Cooling of building integrated PV modules provides protection against degradation or destruction of PV cells, higher efficiency of photovoltaic conversion and surplus low temperature heat gains for use in technical systems of the building.

Analyses have proved that spacing of absorber-cooler risers and thermal conductance of the bond between absorber and pipes should be optimized to achieve high energy production along with low-cost solution of hybrid PV-T collector.

Low temperature of the liquid entering the PV-T collectors (in range of 10 to 25 °C) is a principle condition for their efficient operation with both high thermal and electric energy output. Need for reasonable use of low temperature heat leads to potential application of PV-T concept in water preheating systems or primary circuits of heat pumps.

References

[1] T. Matuska (2008), Advanced solar collectors for building integration. Proceedings of WREC X, pp. 1547-1552, Glasgow (Great Britain).

[2] P. G. Charalambous et al. (2007), Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering 27, pp. 275-286.

[3] Y. Tripanagnastopoulos (2007), Aspects and improvements of hybrid photovoltaic/thermal solar energy systems. Solar Energy 81, 1117-1131.

[4] J. A. Duffie, W.A. Beckman (2006), Solar enginnering of thermal processes. 3. vydání. Wiley 2006, ISBN 13-978-0-471-69867-8.

[5] L. W. Florschuetz (1979), Extension of the Hottel-Whillier model to the analysis of combined photovoltaic/thermal flat plate collectors. Solar Energy, vol. 22, pp. 361-366.

[6] W. C. Swinbank (1963), Long-wave radiation from clear skies. Quarterly Journal of Royal Meteorological Society 89, pp. 339-348.

[7] W. H. McAdams (1954), Heat Transmission, 3rd edition. McGraw-Hill, New York. pp. 249.

[8] E. M. Sparrow, S. C. Lau (1981), Effect of adiabatic co-planar extension surfaces on wind-related solar collector heat transfer coefficients. ASME Journal of Heat Transfer, Vol. 103, pp. 268-271.

[9] R. K. Shah, A. L. London (1978), Laminar flow forced convection in ducts. 1st edition. New York: Academic Press.