MODELING OF GLAZED LIQUID PV-T COLLECTOR WITH USE OF DETAIL MODEL

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ABSTRACT

The paper describes a mathematical model of glazed liquid photovoltaic-thermal (PV-T) solar collector based on detailed construction parameters and energy balance. The model can be used for design analysis and optimization of glazed PV-T collector construction. The mathematical model was experimentally validated for energy performance under steady-state conditions. The model has been implemented as a new TRNSYS type and was used for evaluation of the PV-T collector performance in different climate and operation condition. Influence of glazed PV-T collector design on annual performance of hot water system has been analysed in TRNSYS.

INTRODUCTION

The current trend of using solar energy is focused on maximum utilization of area available on the building. It means to gain maximum amount of energy from one square meter building envelope. This is the main reason why to use multifunctional technology in solar collector field. The photovoltaic-thermal (PV-T) collector converts solar energy into both electric and thermal energy. Usually, state of art photovoltaic (PV) panels have electric efficiency about 15 %, rest of the incident solar radiation is dissipated as waste heat. Hybrid collector can actively deliver the heat for use in system. Due to this, hybrid PV-T collector is able to produce larger amount of energy from the same area than combination of conventional solar thermal collectors and PV panels installed separately.

PV-T liquid collector is the most widely studied configuration because of large potential for the application in buildings. PV-T air collector has limitations with usability of the heat during the summer season. Currently, the market is focused to unglazed PV-T collectors, which are able to generate more electricity compare to conventional PV panels. Although unglazed PV-T collectors are restricted to applications with very low operation temperature like water preheating or coupling the heat pump. The field of solar domestic hot water (SDHW) and space heating applications is rather for the glazed PV-T collectors. Table 1, for better understanding shows a comparison of heat and electricity savings per year for SDHW system in studied variants (Matuska, 2014). The studied SDHW system (100m^2) with hybrid PV-T liquid collectors in different construction concepts is compared with conventional solar heat and power system consisting of state-of-art solar photothermal collectors and PV modules.

Table 1 Results performance analyses for investigated solar energy systems (Matuska, 2014)

Variant	Heat savings [kWh/m^2.a]	Electricity savings [kWh/m^2.a]
PV-T unglazed	127.5	133.6
PV-T glazed	350.3	108.6
Conventional PV panels	-	135.1
Conventional solar collectors	517.3	-

The integration of glazed thermal collector and PV technology into one design changes behaviour of both. The rise of PV cell temperature due to the system operation affects negatively the efficiency of photovoltaic conversion. For unglazed and glazed configuration, commonly crystalline cells are encapsulated in EVA laminate. Although for glazed configuration during stagnation, the EVA lamination starts to degrade and electrical efficiency rapidly falls. Maximum operation temperature for PV-T absorber with EVA laminate is 80 °C (Zondag and Van Helden, 2002). If the temperature is higher, it decomposes to acetic acid, which causes the corrosion of PV cell contacts, delamination and degradation of encapsulation layer transparency. Challenge for future development is to sort out degradation of PV encapsulation because of stagnation temperature for glazed solar collectors from ranges 120 to 180 °C.

Polysiloxane gel has been used as PV cells encapsulation compound for the new prototype of PV-T collector developed in the University Centre for Energy Efficient Buildings (UCEEB), Czech Technical University (Matuska et al, 2014). Polysiloxane gel has numerous advantages compared to EVA: higher transparency for solar radiation, large range of operation temperature (from -60 to +250 °C), low modulus of elasticity, high physical adhesion to semiconductor, higher thermal conductivity (Poulek et al., 2012).

This paper presents a detail numerical model convenient for optimization of the developed glazed PV-T collector design. The model validation is presented, both for electrical performance and thermal performance. An example of performance SDHW system analysis with use of detail model is presented.

PROTOTYPE OF PV-T COLLECTOR

The new prototype of glazed liquid PV-T collector based on new PV cells encapsulation technology was developed and constructed. The construction is based on sandwich structure with monocrystalline PV cells encapsulated in the polysiloxane gel layer between double-glazing (see Fig. 1) and copper sheet with pipe register (conventional solar thermal absorber

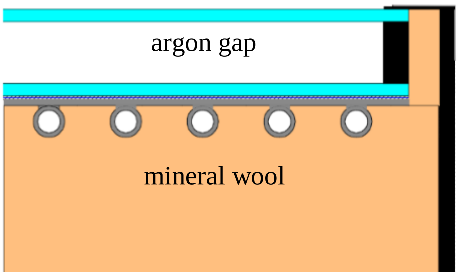

Fig. 1 Developed prototype of PV-T collector

technology). Double-glazing consists from low-iron solar glazings, 4 mm thick, with a gap 24 mm filled with argon. The PV part of the collector consists of 66 cells at size 125 x 125 mm. The PV cell efficiency is 18.6 % under STC (standard test conditions, meaning reference temperature 25 °C and an irradiance 1000 W/m^2 with an air mass 1.5 spectrum). The copper absorber is the sheet and tube configuration. Number of tubes in the hydraulic register is 20. Distance between the tubes is 50 mm. Aperture area of PV-T collector prototype is 1.54 m^2, gross area is 1.71 m^2. Aperture area is filled for 67 % of PV cells (packing factor). Thickness of the thermal insulation on the back side was used 40 mm. All the rest of the parameters of the PV-T collector are in the appendix A1.

Thermal performance of the developed glazed PV-T collector was tested according to EN ISO 9806. Both, for pure thermal mode and the hybrid mode (during electric load for maximum power point conditions). Also the electrical performance was measured in hybrid mode (see Fig. 2) for maximum power point (mpp) conditions.

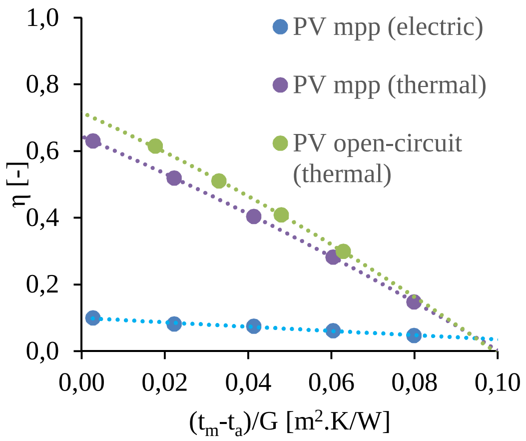

Fig. 2 Thermal and electrical performance of the developed PV-T collector related to gross area

DESCRIPTION OF THE PV-T COLLECTOR MODEL

In order to optimize construction of the glazed PV-T collector, a detailed mathematical model has been developed and implemented into the TRNSYS. Reason of implementation to the TRNSYS was to develop a model, which includes the sufficient amount of parameters for the optimization process. Current model of PV-T collector in TRNSYS type 50b (TRNSYS manual, 2006) does not consider a detailed construction of the collector and change of important collector parameters during the different climate and operational conditions (collector heat loss coefficient, fin efficiency factor, etc.). Currently, exist several steady state models (Duffie, J.A., Beckman, 1991; Bergene and Lovvik; 1995, Zondag et al., 2002) and dynamic models of PV-T collector (Chow, 2003; Haurant et al., 2015). These models are suitable for determination of thermal characteristics of PV-T collector, but they have not been implemented into function of TRNSYS type yet.

Advantage of implemented model is that model calculates energy flow from PV-T absorber surface to ambient and energy flow from PV-T absorber surface to liquid, all in every time step. Following work will be to extend the model by the dynamic part.

The detailed model of glazed PV-T collector allows define a number of construction and physical parameters of collector configuration: geometry, electric properties of PV cells, thermo-physical properties of materials of PV-T collector, etc. Inputs of the model are conventional: climatic and operation conditions. Main outputs of the model are useable thermal and electric power, absorber temperature and outlet temperature. Parameters, inputs and outputs are shown in appendix A1.

Theoretical model

Mathematical model has been developed with use of Florschuetz approach (1979). The model uses energy balance of PV-T collector, expanded for photovoltaic conversion. Calculation procedure of the model solves the external and internal energy balance of the PV-T absorber. Both balances proceeds in the iteration loop.

The photoelectric efficiency to establish electrical performance in Florschuetz approach is estimated as a function of ambient temperature t_a, using the relation of the form

$$\eta_a = \eta_{ref}\left[1-\beta_{ref}(t_a - t_{ref})\right] \quad (1)$$

where β_{ref} is the temperature coefficient of the monocrystalline silicon PV cell, r_c is the packing factor and t_{ref} [°C] is the reference temperature.

The incident energy transformed to heat can be calculated as

$$\tilde{S} = G\cdot\alpha\cdot\tau\cdot\left(1-\frac{\eta_a\cdot r_c}{\alpha}\right) \quad (2)$$

where G [W/m^2] is the incident irradiance, α is the solar absorptance of the PV-T absorber and τ is the transmittivity of the glass cover.

Thermall losses of the PV-T collector can be calculated as presented in eg. (3).

$$\tilde{U} = U - r_c\eta_{ref}\tau G\beta_{ref} \quad (3)$$

where U [W/m^2.K] is the solar collector heat loss coefficient from absorber to ambient.

The collector efficiency factor $\tilde{F}'$ defines the thermal quality of a solar collector. Different absorber configurations result in appropriate equations. For upper bond of absorber to riser pipes the efficiency factor is given as

$$\tilde{F}' = \frac{1/\tilde{U}}{W\cdot\left[\frac{1}{\tilde{U}\left[2a+(W-2a)\cdot F\right]}+\frac{1}{C_b}+\frac{1}{h_i\cdot\pi\cdot D_i}\right]} \quad (4)$$

where W is distance between tubes, C_b [W/m.K] is bond thermal conductance, a is the average bond width and h_i [W/m^2.K] is forced convection heat transfer coefficient in riser pipe.

Heat removal factor $\tilde{F}_R$ is defined as the ratio of the actual heat transfer to the maximum heat transfer and may be written as

$$\tilde{F}_R = \frac{\dot{m}\cdot c}{A_a\cdot\tilde{U}}\left[1-\exp\left(-\frac{A_A\cdot\tilde{U}\cdot\tilde{F}'}{\dot{m}\cdot c}\right)\right] \quad (5)$$

where $\dot{m}$ [kg/h] is the mass flow rate, c [J/kg.K] is the specific heat capacity and A_A [m^2] is the aperture area.

Thermal output $\dot{Q}_t$ [W] is given by

$$\dot{Q}_t = \tilde{F}_R\cdot A_A\left[\tilde{S}-\tilde{U}\cdot(t_{in}-t_a)\right] \quad (6)$$

where t_{in} is the inlet fluid temperature to the collector.

Electrical output $\dot{Q}_e$ [W] is given by

$$\dot{Q}_e = \tau\cdot G\cdot A_A\cdot r_c\cdot\eta_a\cdot \left\{1-\frac{\beta_{ref}\cdot\eta_{ref}}{\eta_a}\cdot\left[\tilde{F}_R(t_{in}-t_a)+\frac{\tilde{S}}{\tilde{U}}\left(1-\tilde{F}_R\right)\right]\right\} \quad (7)$$

MODEL VALIDATION UNDER STEADY STATE CONDITIONS

At the indoor solar simulator, test facility of UCEEB, performance measurements were made (see Fig. 3). Thermal performance on the developed PV-T collector were carried out, according to the solar collector standard EN ISO 9806. All thermal characteristics are related to gross area of the PV-T collector. In the first measurement, PV part was not connected to a maximum power point tracker (thermal mode). The global irradiance has been kept to an average value 1206 W/m^2. The collector tilt angle was set up to 45°. Ambient temperature was fixed at 19 °C. For a water 123 kg/h mass flow, the collector zero loss thermal efficiency was measured at 72 % (related to gross area).

Fig. 3 Tested prototype of PV-T collector

Fig. 4 compares the thermal characteristic calculated by the mathematical model with measured data. In the second measurement the PV part was connected to the maximum power point tracker (hybrid mode). The global irradiance has been kept at the average value 931 W/m^2. The collector tilt angle was set up to 45°. Ambient temperature was fixed at 17 °C. For a water 123 kg/h mass flow, the collector zero loss thermal efficiency was measured at 63 % and the electrical efficiency at 9.1 % (related to gross area).

Fig. 5 compares the thermal characteristic calculated by the mathematical model with measured data. Electrical power generation was also measured under steady state conditions for five different inlet temperatures. Fig. 6 compares the maximum electrical power output calculated by the mathematical model with measured data.

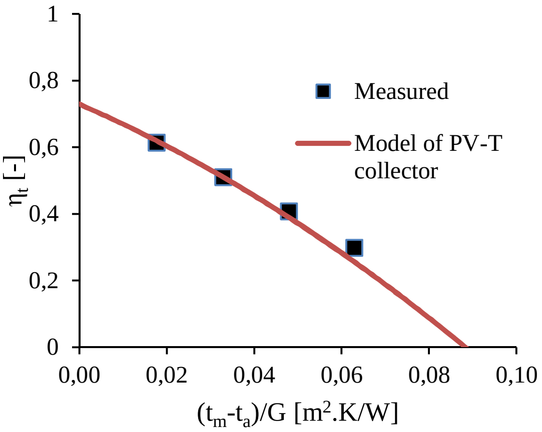

Fig. 4 Measured and calculated thermal performance in thermal mode

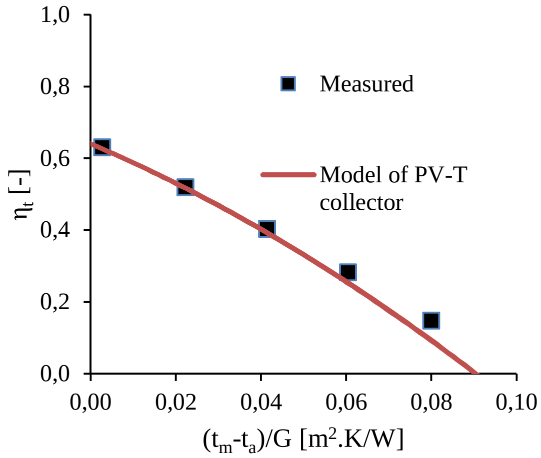

Fig. 5 Measured and calculated thermal performance in hybrid mode

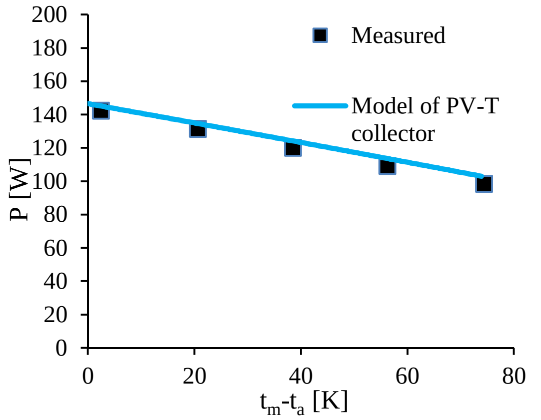

Fig. 6 Measured and calculated maximum electrical power point

ANALYSIS OF PV-T COLLECTOR PERFORMANCE

Mathematical model is convenient to use for unrealized prototype of PV-T collector. The model allows observation of the influence of thermal and electrical performance changes. The advantage of the mathematical model is that energy balance of PV-T collector calculates for every time-step of simulation. Moreover, it is possible to optimize the solar hot domestic water (SDHW) installation and other coupled energy system.

Analysis was focused on optimization of usage of low emissivity coating and thickness of the insulation (back side). Whether it has a greater impact on the thermal performance of PV-T collector to increase thickness of the insulation or to change the coating of the PV-T absorber. Possible approach is to use spectrally selective low emissivity (low-e) coatings, which have high reflectance in the infrared spectrum similar to absorber coatings for conventional solar thermal collectors. In the visible part of spectrum has low-e coating lower transmittance. For the scope of this analysis, two variants of the PV-T absorber were simulated with three different thickness of insolation (30 mm, 40 mm, 50 mm). First variant is nonselective absorber (absorptance was 0.92 and front surface emissivity of PV-T absorber was 0.84). Second variant is selective PV-T absorber with low-e coating on the front surface of PV-T absorber (absorptance was 0.89 and front surface emissivity of PV-T absorber was 0.3). For this case was used manufactured double-glazing with overall transmittance 0.86 (Euroglass). Inside of the PV-T collector, the low-e coating is applied above the surface of the PV-T absorber (inner glass of the double-glazing). Comparison of thermal and electrical characteristics for both variants of PV-T absorber is shown in Fig. 7.

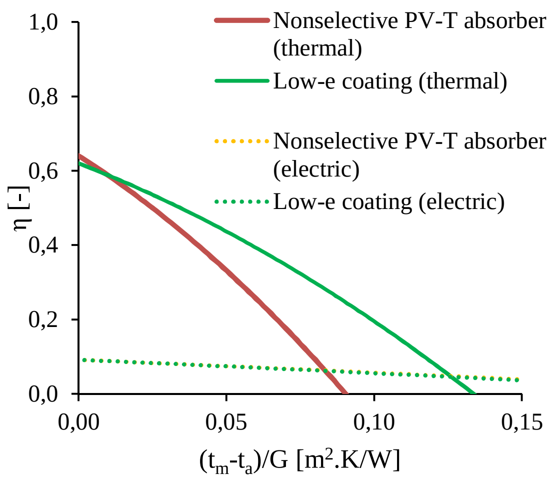

Fig. 7 Comparison of thermal and electrical characteristics

Description of the SDHW system

PV-T collector has been evaluated as a part of a solar thermal system. The thermal performance of PV-T collector depends on the energy demand. Electrical energy is directly fed into the public electrical network. Components of SDHW system are listed in Table 2.

Table 2
List of the TRNSYS types in the SDHW simulation deck

COMPONENT	TYPE
PV-T collector	developed type 223
Controller	Type 2b
Load profile data reader	Type 14h
Flow diverter	Type 11b
Tee piece	Type 11h
Pump	Type 3b
Tank	Type 4c

Main parameters used in SDHW simulation

- Collector area was 3.42 m^2, south orientation, 45° inclination.
- Flow rate of 40 $kg/h.m^2$.
- Water storage was 200 l.
- DHW consumption 200 l of 55 °C heated water per day.
- Weather conditions for Prague

Area of the solar system was designed due to the middle Europe experiences that show the solar fraction from 45 % to 70 % for SDHW systems is an economical optimal solution.

Simulation results

Table 3
Results of the simulation for nonselective absorber

NONSELECTIVE ABSORBER		
Thickness of the insolation 30 mm	Electrical energy production	367 kWh/year
	Thermal energy production	1122 kWh/year
	Solar fraction	44 %
Thickness of the insolation 40 mm	Electrical energy production	366 kWh/year
	Thermal energy production	1338 kWh/year
	Solar fraction	44.7 %
Thickness of the insolation 50 mm	Electrical energy production	366 kWh/year
	Thermal energy production	1147 kWh/year
	Solar fraction	44.8 %

Table 4
Results of the simulation for selective absorber

SELECTIVE ABSORBER		
Thickness of the insolation 30 mm	Electrical energy production	363 kWh/year
	Thermal energy production	1247 kWh/year
	Solar fraction	48.7 %
Thickness of the insolation 45 mm	Electrical energy production	362 kWh/year
	Thermal energy production	1269 kWh/year
	Solar fraction	49.6 %
Thickness of the insolation 55 mm	Electrical energy production	362 kWh/year
	Thermal energy production	1280 kWh/year
	Solar fraction	50 %

Energy production for two types of PV-T absorber was simulated. The increase of thermal energy production is approximately 10 %, due to the low-e coating. Electrical energy production is slightly lower than nonselective absorber (2 % lower). The radiative losses are significantly reduced by the low-e coating, therefore the thermal characteristic has lower inclination. At the same time, transmittance of solar radiation is reduced for PV cells. Due to the reduced solar radiation for PV cells the electrical energy production is slightly lower. The increase of thermal energy production, due to thicker insolation is approximately 1 %. The difference for electrical energy production is even lower.

CONCLUSION

Implemented mathematical model into the TRNSYS allows to use climatic data for whole year, due to the analyses are more complex. Mathematical model was validated under steady state conditions, both for the thermal and the electrical performance. After the outdoor test stand is built, the mathematical model can be validated in real (dynamic) conditions.

Analyses showed that the thermal energy production is much higher with low-e coating and without high losses of electric energy production. The analyses also confirmed that from the financial standpoint, to increase thickness of insolation does not make sense. Increase of thermal energy production due to the thicker insolation is only 1 %. Next step in development of PV-T collector will be to construct prototype with low-e coating. Application of laminate glazing with a spectrally selective coating could reduce the radiation heat loss and improve the thermal properties of the glazed PV-T collector.

NOMENCLATURE

a	average bond width [m]
A_A	aperture area [m]
c	specific heat capacity [J/kg.K]
C_b	bond thermal conductance [W/m.K]
F	fin efficiency factor [-]
$\tilde{F}'$	PV-T collector efficiency factor [-]
$\tilde{F}_R$	heat removal factor [-]
G	incident radiation [W/m^2]
h_i	forced convection heat transfer coefficient in riser pipe [W/m^2.K]
$\dot{Q}_e$	electrical power output [W]
$\dot{Q}_t$	thermal output [W]
r_c	packing factor [-]
$\tilde{S}$	incident energy transformed to heat [W/m^2]
t_a	ambient temperature [°C]
t_{in}	inlet fluid temperature [°C]
t_{ref}	reference temperature [°C]
U	collector heat loss coefficient [W/m^2.K]
$\tilde{U}$	PV-T collector heat loss coefficient [W/m^2.K]
W	distance between tubes [-]
α	solar absorptance [-]
β_{ref}	temperature coefficient of electrical efficiency [-]
η_{ref}	reference electrical efficiency [-]
η_a	electrical efficiency at ambient temperature [-]
τ	normal solar transmittance [-]

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APPENDIX A.

Table 5
Trnsys type (values are valid for prototype)

NAME	VALUE	UNIT
INPUTS		
Incident radiation	variable	W/m^2
Ambient temperature	variable	°C
Wind velocity	variable	m/s
Mass flow rate	variable	kg/h
Inlet fluid temperature	variable	°C
Incidence angle	variable	°
PARAMETERS		
Slope angle	45	°
Adjacent frontal surface	0,9	-
Gross height	1,043	m
Gross length	1,642	m
Aperture height	0,978	m
Aperture length	1,571	m
Gap between glazing and PV-T absorber	0,024	m
Gap between PV-T absorber and Frame	0	m
Gas pressure between glazing and PVT absorber	100	kPa
Thermal conductivity of the PV-T absorber	350	W/m.K
Thickness of absorber	0,0002	m
Solar absorptance	0,93	-
Front surface emissivity of absorber	0,84	-
Back surface emissivity of absorber	0,9	-
Length of riser pipes	1,515	m
Number of riser pipes	20	-
Distance between the pipes	0,05	m
Pipe internal diameter	0,0072	m
Average bond width	0,003	m
Average bond thickness	0,001	m
Thermal conductivity of bond	350	W/m.K
Mixing ratio of propylene glycol in water	0	-
Thickness of Glass	0,004	m
Thermal conductivity of glass	0,8	W/m.K
Normal solar transmittance	0,91	-
External surface emissivity of glass	0,84	-
Internal surface emissivity	0,84	-
Thickness of insulation	0,04	m
Thermal conductivity of insulation	0,034	W/m.K
External frame surface emissivity	0,5	-
Internal frame surface emissivity	0,5	-
Thickness of insulation (lateral side)	0,02	m
Thermal conductivity of insulation (lateral side)	0,034	W/m.K
Reference electrical efficiency	0,186	-
Temperature coefficient of PV cell efficiency	0,0043	-
1-st order IAM	0,15	-
Gas layer between glazing	Argon	-
Number of collectors	1	-
Packing factor	0,67	-
OUTPUTS		
Outlet mass flow rate	variable	kg/h
Thermal energy gain	variable	W
Electrical power output	variable	W
Outlet fluid temperature	variable	°C
Absorber temperature	variable	°C