Performance Analysis of Glazed Liquid Photovoltaic-thermal Collector with Use of Detail Model

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Abstract

The current trend of using solar energy is focused on maximum utilization of area available on the building envelope. Therefore the interest in multifunctional technology in solar collector field increases. The photovoltaic-thermal (PVT) collector converts solar energy into both electric and thermal energy. The paper describes the mathematical model of glazed liquid PVT solar collector based on detailed construction parameters and energy balance. The model can be used for design analysis and optimization of glazed PVT collector construction. The mathematical model was experimentally validated for thermal and electric energy performance under steady-state conditions. The model has been implemented as a new component in TRNSYS simulation environment and has been used for evaluation of the PVT collector performance in different climate and operation conditions. Influence of glazed PVT collector design on annual performance of domestic hot water system was analysed with use of TRNSYS. The results of the annual simulations were used for decision on the design of final glazed PVT collector prototype.

Keywords: Solar energy; mathematical model; glazed PVT collector; TRNSYS

1. Introduction

The photovoltaic-thermal (PVT) collector converts solar energy into both electric and thermal energy. Usually, state of the 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 PVT 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.

The PVT liquid collector is the most widely studied configuration because of large potential for the application in buildings. The PVT air collector has limitations with usability of the heat during the summer season. Currently, the market is focused on unglazed PVT collectors which are able to generate more electricity compare to conventional PV panels. Although unglazed PVT 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 PVT collectors. Table 1, for better understanding shows a comparison of heat and electricity savings per year for SDHW system in studied variants [1]. The studied SDHW system ($100 m^2$) with hybrid PVT liquid collectors in different construction concepts was compared with conventional solar heat and power system consisting of state-of-art solar photothermal collectors and PV modules. 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 ethylene-vinyl acetate (EVA) laminate. Although for glazed configuration during stagnation, the EVA lamination starts to degrade and electrical efficiency rapidly falls. Maximum operation temperature for PVT absorber with EVA laminate is 80 °C [2]. 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 solve degradation of PV encapsulation because the stagnation temperature for glazed solar collectors is from ranges 120 to 180 °C.

Table 1 *Results of performance analyses for investigated solar energy systems [1]*

Variant	**Heat savings [$kWh.m^{-2}.a^{-1}$]**	**Electricity savings [$kWh.m^{-2}.a^{-1}$]**
PVT glazed	127	133
PVT unglazed	350	108
Conventional PV panels	-	135
Conventional solar collectors	517	-

Polysiloxane gel has been used as PV cells encapsulation compound for the new prototype of PVT collector developed in the University Centre for Energy Efficient Buildings (UCEEB), Czech Technical University [1].

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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 [3].

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

2. Prototype of the PVT collector

The new prototype of glazed liquid PVT 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 technology).

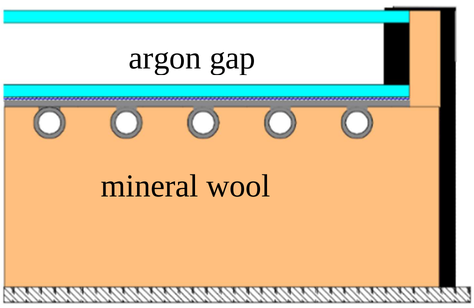

Fig. 1 *Layout of the PVT collector*

Double-glazing consists from the 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 $W \cdot m^{-2}$ 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 PVT collector prototype is 1,5 m^2, gross area is 1,7 m^2. Aperture area is filled for 67 % of PV cells (packing factor). Thickness of the thermal insulation on the back side was 40 mm.

Thermal performance of the developed glazed PVT collector was tested according to EN ISO 9806. The PVT collector was tested 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.

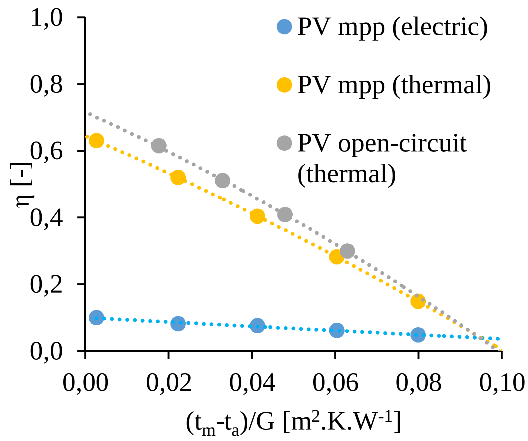

Fig. 2 *Thermal and electrical efficiency of the developed PVT collector related to gross area*

3. Mathematical model of the PVT collector

In order to optimize construction of the glazed PVT 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 PVT collector in TRNSYS is type 50b [4] which 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 [5, 6] and dynamic models of glazed PVT collector [7, 8]. These models are suitable for determination of thermal characteristics of PVT collector, but they have not been implemented into function of TRNSYS type yet. The advantage of implemented model is that model calculates energy flow from PVT absorber surface to ambient and energy flow from PVT 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 PVT 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 PVT collector, etc. Inputs of the model are conventional: climatic and operation conditions. Main outputs of the model are: thermal output, electric power, absorber temperature, and outlet temperature.

3.1. Theoretical model

Mathematical model has been developed with use of Florschuetz approach [9]. The model uses energy balance of PVT collector, expanded for photovoltaic conversion. Calculation procedure of the model solves the external and internal energy balance of the PVT 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

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

where β_{ref} [-]is the temperature coefficient of the mono-crystalline 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

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

where G [W·m^{-2}] is the incident irradiance, α [-] is the solar absorptance of the PVT absorber and τ [-] is the transmittance of the glass cover.
Thermal losses of the PVT collector can be calculated as presented in eq. (3).

$$\tilde{U} = U - r_c\eta_{ref}\tau G\beta_{ref} \tag{3}$$

where U [W·m^{-2}·K^{-1}] 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

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

where W is distance between tubes, C_b [W·m^{-1}·K^{-1}] is bond thermal conductance, a [m] is the average bond width and h_i [W·m^{-2}·K^{-1}] 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

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

where $\dot{m}$ [kg·h^{-1}] is the mass flow rate, c [J·kg^{-1}·K^{-1}] is the specific heat capacity and A_A [m^2] is the aperture area.
Thermal output $\dot{Q}_t$ [W] is given by

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

where t_{in} [°C] is the inlet fluid temperature to the collector.
Electrical output $\dot{Q}_e$ [W] is given by

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

4. 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 PVT collector were carried out, according to the solar collector standard EN ISO 9806.

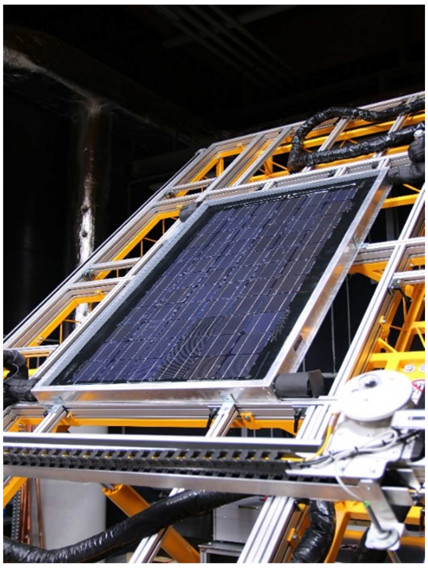

Fig. 3 *Tested prototype of the PVT collector*

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^{-1} mass flow, the collector zero loss thermal efficiency was measured at 72 % (related to gross area). In the second measurement the PV part was connected to the mpp tracker (hybrid mode). The global irradiance was kept at the average value 931W·m^{-2}. The collector tilt angle was set up to 45°. Ambient temperature was fixed at 17 °C. For a water 123 kg·h^{-1} mass flow, the collector zero loss thermal efficiency was measured at 63 % and the electrical efficiency at 9.1 % (related to gross area). Efficiency characteristics have been modelled as two boundary lines expressing the uncertainty of input data (insulation conductivity, absorber conductivity, optical properties, etc.) used in model (see Fig. 4). For example measurement uncertainty of thermal conductivity of insulation is about 10 %, for properties of glazing is measurement uncertainty about 2 % (emissivity, transmittance). Uncertainty of dimension parameter was not considered. The experimental data derived for steady state laboratory test in hybrid mode (use of mpp tracker) lie within the borders, however there is still need to improve the model further. Following work will be to validate mathematical model under real climatic conditions.

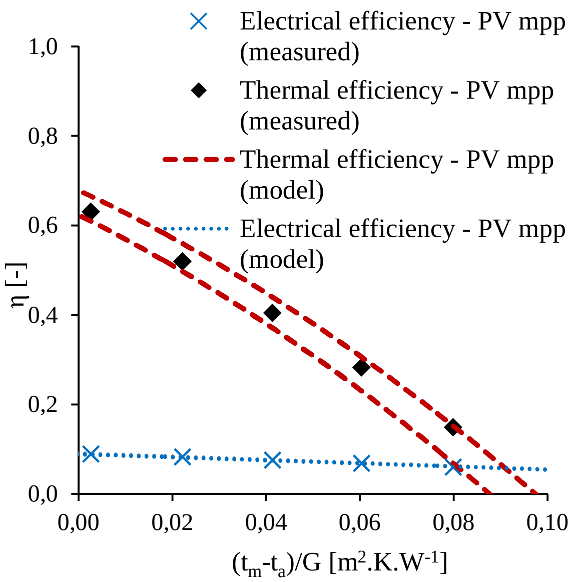

Fig. 4 *Measured and calculated thermal and electrical performance in hybrid mode*

4. Performance analysis of PVT collector

The mathematical model is convenient to use for development of unrealized prototype of PVT collector. The model allows observation of influence of different collector design on thermal and electrical performance. The advantage of the mathematical model is that energy balance of PVT collector calculates for every time-step of simulation. Moreover, it is possible to optimize the SDHW system and other coupled energy system.

Analysis was focused on optimization of usage of low emissivity coating, different levels of thickness of the insulation (back side), and different levels of thickness of the air gap (gap between PVT absorber and cover glazing). Whether, it has a greater impact on the thermal and electrical performance of PVT collector to increase thickness of the insulation (air gap) or to change the coating of the PVT absorber. The purpose of this study is to optimize PVT collector design. In case of coating analysis, 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 and near infrared part of spectrum low-e coating has lower transmittance. For the scope of this analysis, two variants of the PVT absorber were simulated with four different thickness of insulation (20 mm, 30 mm, 40 mm, 50 mm) and with four different thickness of air gap (10 mm, 20 mm, 30 mm, 40 mm). First variant is nonselective absorber (absorptance was 0.92 and front surface emissivity of PVT absorber was 0.84). Second variant is selective PVT absorber with low-e coating on the front surface of PVT absorber (absorptance was 0.89 and front surface emissivity of PVT absorber was 0.3). For this case, it was used optical properties of manufactured double-glazing with overall transmittance 0.86 (Euroglas) developed by Giovannetti et al. [10]. Inside of the PVT collector, the low-e coating is applied above the surface of the PVT absorber (inner glass of the double-glazing, see in Fig. 1). Comparison of thermal and electrical characteristics for both variants of PVT absorber is shown in Fig. 5. Thermal efficiency of PVT collector with selective coating (green) performs applicability over higher operating temperatures thanks to lower radiative losses.

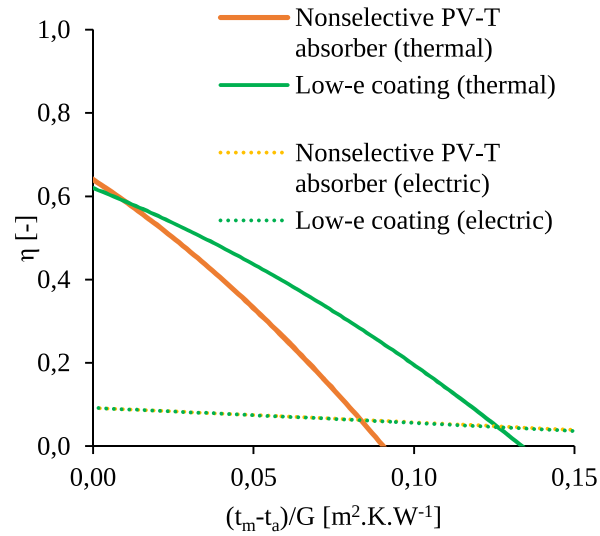

Fig. 5 *Comparison of thermal and electrical characteristics*

4.1. Description of the SDHW system

Glazed PVT collector has been evaluated as a part of a solar thermal system. The thermal performance of PVT collector depends on the energy demand. Electrical energy is directly fed into the public electrical network. The solar thermal part of the investigated system consists of several main components: glazed PVT collectors, insulated solar DHW storage, etc.

Main parameters used in SDHW simulation

- Collector area was 6,8 m^2 (1,043 x 1,642 m), south orientation, 45° inclination.
- Flow rate of 40 $kg.h^{-1}.m^{-2}$.
- Water storage was 340 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.

4.2. Simulation results

One reference PVT collector (RPC) design was chosen (bold font). The others levels of thickness are consider as variables. Energy production for two types of PVT absorber was simulated (see Tab. 1 to Tab. 4). The increase of thermal energy production is approximately 8 %, 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 in thermal energy production, due to thicker insulation is approximately 1 % (see Tab. 1 and Tab. 2). Regarding the electrical energy production the difference is even lower.

Table 2 *Results of the simulation for nonselective absorber and different thickness of the insulation*

Nonselective PVT absorber		
Thickness of the insulation	**Thermal energy production**	**Electrical energy production**
20 mm	1615 $kWh \cdot a^{-1}$	651 $kWh \cdot a^{-1}$
30 mm (RPC)	**1651 $kWh \cdot a^{-1}$**	**648 $kWh \cdot a^{-1}$**
40 mm	1668 $kWh \cdot a^{-1}$	646 $kWh \cdot a^{-1}$
50 mm	1678 $kWh \cdot a^{-1}$	645 $kWh \cdot a^{-1}$

Table 3 *Results of the simulation for selective absorber and different thickness of the insulation*

Selective PVT absorber		
Thickness of the insulation	**Thermal energy production**	**Electrical energy production**
20 mm	1757 $kWh \cdot a^{-1}$	636 $kWh \cdot a^{-1}$
30 mm (RPC)	**1803 $kWh \cdot a^{-1}$**	**631 $kWh \cdot a^{-1}$**
40 mm	1826 $kWh \cdot a^{-1}$	628 $kWh \cdot a^{-1}$
50 mm	1838 $kWh \cdot a^{-1}$	627 $kWh \cdot a^{-1}$

Increase in thermal energy production, due to thicker air gap is significant between 10 and 20 mm (12 %), see in Tab. 1 and 2. Thermal energy production for thicker air gap than 20 mm is negligible. Decrease in electrical energy due to thicker air gap is insignificant (less than 0,1 %).

Table 4 *Results of the simulation for selective absorber and different thickness of the air gap*

Nonselective PVT absorber		
Thickness of the air gap	**Thermal energy production**	**Electrical energy production**
10 mm	1447 $kWh \cdot a^{-1}$	661 $kWh \cdot a^{-1}$
20 mm (RPC)	**1649 $kWh \cdot a^{-1}$**	**648 $kWh \cdot a^{-1}$**
30 mm	1651 $kWh \cdot a^{-1}$	648 $kWh \cdot a^{-1}$
40 mm	1656 $kWh \cdot a^{-1}$	647 $kWh \cdot a^{-1}$

Table 5 *Results of the simulation for selective absorber and different thickness of the air gap*

Selective PVT absorber		
Thickness of the air gap	**Thermal energy production**	**Electrical energy production**
10 mm	1543 $kWh \cdot a^{-1}$	652 $kWh \cdot a^{-1}$
20 mm (RPC)	**1802 $kWh \cdot a^{-1}$**	**631 $kWh \cdot a^{-1}$**
30 mm	1803 $kWh \cdot a^{-1}$	631 $kWh \cdot a^{-1}$
40 mm	1807 $kWh \cdot a^{-1}$	630 $kWh \cdot a^{-1}$

Based on the results of the simulations convenient variant of the selective PVT collector (thickness of the insulation 30 mm and thickness of the air gap 20 mm) was chosen.

5. Conclusion

Mathematical model has been implemented into the TRNSYS environment. Implemented model 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 will be 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 energy point of view, to increase thickness of insulation more than 30 mm does not make sense. Increase of thermal energy production due to the thicker insulation more than 30 mm is only 1 %. Next step in development of PVT 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 PVT collector.

Acknowledgement

The paper has been supported by European Union project OP VaVpI no. CZ.1.05/2.1.00/03.0091 – University Centre for Energy Efficient Buildings.

Nomenclature

a	average bond width (m)
A_A	aperture area (m)
c	specific heat capacity (J·kg^{-1}·K^{-1})
C_b	bond thermal conductance (W·m^{-1}·K^{-1})
F	fin efficiency factor (-)
$\tilde{F}'$	PVT 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^{-1})
$\dot{m}$	mass flow rate (kg·h^{-1})
$\dot{Q}_e$	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^{-1})
$\tilde{U}$	PVT collector heat loss coefficient (W·m^{-2}·K^{-1})
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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