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MONITORING OF SOLAR DOMESTIC HOT WATER SYSTEM WITH GLAZED LIQUID PVT COLLECTORS

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Abstract

Glazed liquid photovoltaic-thermal collectors with polysiloxane encapsulation of photovoltaic cells have been developed and fabricated to generate both electric and heat energy simultaneously. The purpose of this study is to present the monitoring of the solar domestic hot water system with the new photovoltaic-thermal collector prototypes and compare the results with data simulated by a dynamic mathematical model of glazed liquid photovoltaic-thermal collector. The detailed dynamic model enables the optimization of the construction design and has been implemented into TRNSYS as a new type to allow the system simulations. Experimental measurement of solar domestic hot water system with two glazed photovoltaic-thermal collectors has been done for 6 days. Thermal energy difference for whole measured period of monitoring was less than 1.5 % compare to dynamic model. Difference between measured electric energy output and modelled was 8.1 %.

Keywords: *Solar energy, glazed PVT collector, SDHW system*

1. Introduction

Hybrid solar photovoltaic-thermal (PVT) collectors have attracted a large interest in last decade. Increase of energy production from given receiving area at the building envelope can bring higher solar fractions both for electricity and heat demand. While unglazed PVT collectors show excellent electric yields, their poor thermal performance results in lower total energy production when compared with combination of conventional PV modules and photothermal collectors(Matuska, 2014). Glazed PVT collectors could offer a good compromise between electricity and heat production, the total energy production is higher than for conventional combination of identical area (Matuska et al., 2015). The principle barrier for the glazed PVT collectors development is the weak resistance of common ethylene-vinyl acetate (EVA) encapsulation to excessive thermal exposure. Maximum operation temperature of EVA laminate is around 85 °C (Zondag et al., 2002) while the stagnation temperature for glazed solar collectors ranges from 120 to 180 °C. At these temperatures EVA encapsulation decomposes to acetic acid, which causes the corrosion of PV cell contacts, delamination and degradation of layer transparency. Nevertheless, majority of published papers focused on development of new glazed PVT collectors consider PV cells encapsulated in EVA lamination (Zondag et al., 2002; Chow et al., 2006; Dupeyrat et al., 2011). Research in the area of glazed PVT collectors resulted into two approaches. One is focused on the increasing heat losses during stagnation period (Lammle et al., 2016) and second focuses on the temperature resistant material as replacement for EVA lamination (Matuska, 2014). In this paper new concept of solar PVT collectors is presented where PV cells are encapsulated between double glazing and metal heat exchanger by means of polysiloxane gel. Polysiloxane gel as PV encapsulant offers a large range of operation temperatures (from -60 to +250 °C), high transparency for solar radiation and allows the compensation of thermal dilatation stresses thanks to low modulus of elasticity (Poulek et al., 2012).

Developed PVT collector presented in this paper uses temperature resistant material as encapsulant for PV cells. Moreover, the paper presents a detailed numerical model convenient for the optimization of glazed PVT collector design. Several glazed solar PVT collector prototypes based on the polysiloxane encapsulant have

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been fabricated. Prototypes have been tested in outdoor conditions and under conditions of artificial sun. The developed mathematical model has been validated for steady-state conditions (Pokorny et al., 2015) both for electrical and thermal performance and it has been implemented into TRNSYS as a new type. Reason of the implementation to the TRNSYS was to have a model which includes sufficient amount of parameters for the optimization in the PVT collector design process (glazing properties, dimensions and physical properties of sheet and tube absorber, properties of insulation etc.). Currently available types in TRNSYS is type 563 (unglazed) and type 50 (glazed). Only type 50 is suitable for glazed PVT collectors but type 50 do not consider a detailed construction parameters of the collector as well as do not consider change of important collector parameters during the varying operation conditions. Several steady-state models (Bergene and Løvvik, 1995; Zondag et al., 2002)and dynamic models of glazed PVT collector (Chow, 2003; Haurant et al., 2015; Guarracino et al., 2016) were published but not available for TRNSYS. The work presented here extends the steady-state model by a dynamic term to allow the system performance simulations at realistic conditions. The new type has been used for the simulation of solar domestic hot water system and the results were compared with an experimental installation of solar DHW system equipped with the developed glazed PVT collectors.

2. Theoretical model of glazed liquid PVT collector

In order to optimize construction of the glazed PVT collector, a detailed mathematical model has been developed and implemented into the TRNSYS. 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. The detailed model of glazed PVT collector allows to define a number of construction and physical parameters of collector configuration. Inputs of the model are climatic and operation conditions. Main outputs of the model are: thermal output, electric output, absorber temperature and outlet temperature. For instance, type 50 available in TRNSYS has effective heat loss (eq. 3) constant for whole simulation. Equally collector efficiency factor (eq. 4) is constant because model does not consider variable forced convection in pipes. Also type 50 does not consider thermal capacity of the PVT collector. Mathematical model of glazed PVT collector has been developed on the basis of Florschuetz approach (1979)). A detailed calculation of the heat transfer from the collector absorber to ambient (heat loss) and from the collector absorber to the heat transfer liquid (internal balance) is performed within the iterative loops. The model inputs are the detailed geometrical, thermal, electrical and optical properties (about 40 parameters) of individual segments of the PVT collector together with operation and climatic conditions. Temperature distribution in the solar collector is calculated in the iteration loops. Original steady-state model has been extended to a dynamic model by the introduction of the effective thermal capacity term available from testing or calculation. The dynamic term is used for the thermal calculations, the calculation of the electric output doesn't consider dynamic change of the temperature in the PVT collector so far. Moreover, non-uniform distribution of PV cells temperature which could have impact on the electric performance is not taken into account in the electric part of the model.

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

$$\eta_a = \eta_{ref}\left[1-\beta_{ref}(t_a - t_{ref})\right] \qquad \text{(eq. 1)}$$

where β_{ref} [-] is the temperature coefficient of the PV cells, η_{ref} is the reference efficiency of PV cells, and t_{ref} [°C] is the reference temperature, all at standard testing conditions (STC). The incident solar energy converted to heat can be calculated as

$$\tilde{S} = G \cdot \alpha \cdot \tau_g \cdot \left(1 - \frac{\eta_a \cdot r_c}{\alpha}\right) \qquad \text{(eq. 2)}$$

where G [W·m^{-2}] is the incident irradiance, α [-] is the solar absorptance of the PVT absorber, τ_g [-] is the transmittance of the glass cover and r_c [-] is the packing factor (related to aperture area).

Effective heat loss coefficient of the PVT collector can be calculated as

$$\tilde{U} = U - r_c \eta_{ref} \tau_g G \beta_{ref} \qquad \text{(eq. 3)}$$

where U [W·m^{-2}·K^{-1}] is the PVT collector heat loss coefficient from absorber to ambient related to aperture area. The collector efficiency factor $\tilde{F}'$ [-] for upper bond of absorber to riser pipes is given as

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

where W is distance between risers, 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 the riser pipe.

Heat removal factor $\tilde{F}_R$ [-] is defined as

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

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

$$\dot{Q}_t=\tilde{F}_R\cdot A_a\left[\tilde{S}-\tilde{U}\cdot(t_{in}-t_a)\right]-C\cdot A_a\cdot\frac{dt_m}{d\tau} \quad \text{(eq. 6)}$$

where t_{in} [°C] is the inlet fluid temperature to the collector, C [J.m^{-2}.K^{-1}] is the effective thermal capacity of PVT collector, t_m [°C] is mean fluid temperature, and $d\tau$ is time step of simulation. Electric output $\dot{Q}_e$ [W] is given by formula

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

3. Steady-state testing of prototypes and model validation

The prototypes of glazed liquid PVT collector have been developed and constructed based on the new concept (Matuska, 2014)to be further investigated and used for the validation of the mathematical model. 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). Double glazing with a gap between glass panes 24 mm filled with argon has been used. No optical coatings have been applied for glass surfaces. Transmittance of the glazing is 0.91 and emissivity of the PVT absorber is 0.84. Average absorptance of the PVT absorber is 0.93. In total 6 x 11 polycrystalline PV cells at size 125 x 125 mm have been used. Gross area of the collector has been filled with PV cells for 60 % (packing factor related to gross area). Absorber has been made from copper sheet (0.2 mm) soldered to pipe register made from risers of 8 mm in diameter with thermal conductivity 200 W.m^{-1}.K^{-1}. Distance between the copper risers was 50 mm. Absorber has been insulated by 30 mm of mineral wool on the back, edge side was insulated by 10 mm of mineral wool (thermal conductivity 0.04 W.m^{-1}.K^{-1}). The frame of the PVT collector has been made of aluminum profiles.

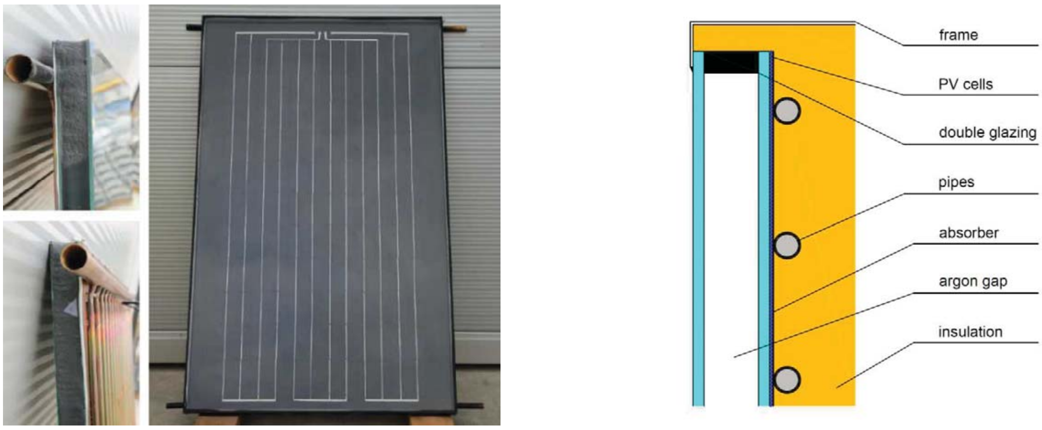

Fig. 1: Compact sandwich of double glazing, encapsulated PV cells and copper heat exchanger (left) and the schematic layout of the whole PVT collector (right)

The sample of developed glazed PVT collector have been tested at Solar laboratory (UCEEB CTU) with use of indoor solar simulator. Solar simulator consist of 8 metal halide lamps with power 4.5 kW. Solar simulator can achieve irradiance up to 2000 W.m^{-2} with guaranteed homogeneity 5 % on the area 1 x 2 m. Required inlet temperature to the collector is supplied by thermostat with tolerance ±0.03 K. The thermal performance has been determined according to EN ISO 9806. Required accuracy of measurement according to EN ISO 9806 was respected. Characteristic of thermal efficiency has been tested in two modes. In the hybrid mode, the PV part was connected to MPP tracker with measured load. In open circuit mode, the PVT collector thermal performance was tested without electric load. Thermal and electric characteristics have been related to gross area of the PVT collector which is 1.71 m^2 (1.04 m x 1.64 m). The global irradiance was kept at the average value 931 W.m^{-2} during the test. The collector tilt angle was set up to 45°. Ambient temperature was fixed at 17 °C. Collector zero loss thermal efficiency was evaluated 65 % and the electrical efficiency 9.1 % (both related to gross area). Moreover, the thermal capacity of the PVT collector was assessed 14.5 kJ.m^{-2}.K^{-1} by the testing.

Individual electric test of the PV part of PVT collector was carried out with PASAN tester at standard test conditions (G = 1000 W.m^{-2}, t = 25 °C, AM1,5). The results of the PV test are: U_{OC} = 40.7 V, I_{SC} = 5.1 A, U_{MPP} = 31,4 V, I_{MPP} = 4.81 A, P_{MPP} = 151 W, η_{STC} = 8.8 %.

To validate the mathematical model the thermal and electric efficiency characteristics have been modelled and compared to steady-state tested data. There is natural uncertainty in the parameters data for the model, e.g. real thermal conductivity of the insulation, real transmittance of the cover glazing, real absorptance and emissivity of the full absorber area, etc. For example, uncertainty of thermal conductivity value for the insulation could be considered about 10 % if not determined from special testing, transmittance of cover glazing was considered with uncertainty about 2 % according to datasheet of the manufacturer, etc. Therefore the efficiency characteristics have been modelled as two boundary lines expressing the full range of parameters uncertainty and creates the model uncertainty band for given PVT collector. This band could be diminished if there is a knowledge of the parameters with better precision. The experimental data derived for steady-state laboratory test of the PVT collector in hybrid mode lie within the model uncertainty band (see Fig. 2, red lines), however there is still potential to improve the model further.

The measurement uncertainty of thermal efficiency was determined by methodology published in (Mathioulakis et al., 1999). Results of experimental uncertainties are in Tab 1. Uncertainty of the model is much bigger compare to uncertainties of the measurement. For this reason uncertainties were not plotted in the chart in Fig. 2.

Tab. 1: Measurement uncertainties for thermal efficiency (related to gross area)

	η	$\eta + \sigma$	$\eta - \sigma$
η_0 [-]	0,645	0,649	0,640
a_1 [$W.m^{-2}.K^{-1}$]	5,391	5,141	5,640
a_2 [$W.m^{-2}.K^{-2}$]	0,011	0,008	0,014

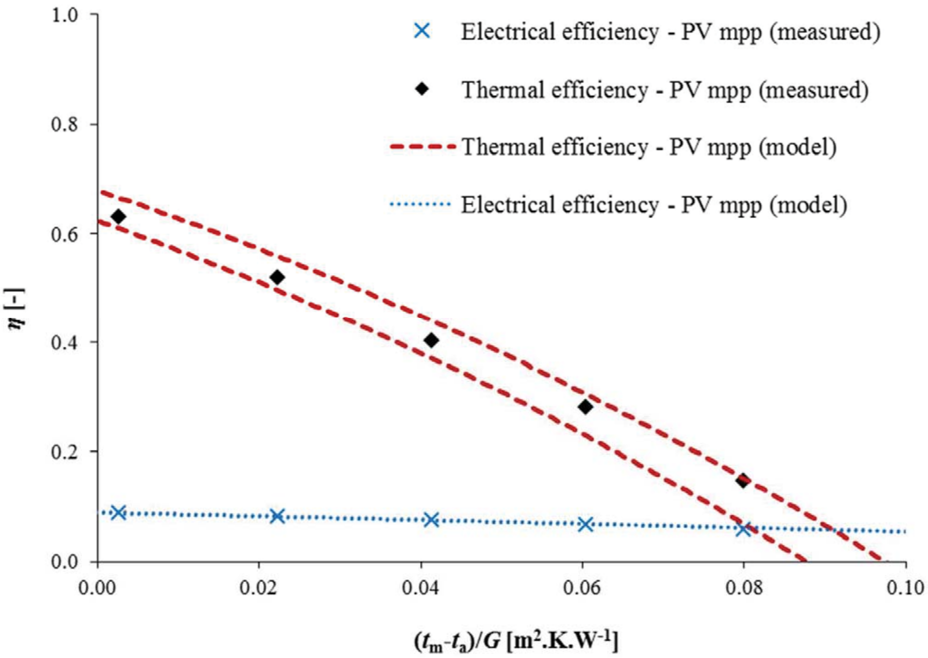

Fig. 2: Measured and calculated thermal and electrical performance in hybrid mode under steady state conditions

4. Solar system with glazed PVT collectors

Solar domestic hot water system with glazed nonselective PVT collectors has been realized to prove the applicability of the technology in real environment. Moreover, the developed dynamic model has been used for parallel simulation of the energy output in TRNSYS to continue with the validation process. PVT collectors were installed in the outdoor part of Solar laboratory on the roof of the Faculty of Mechanical Engineering, CTU in Prague and rest of the technology was placed in the adjacent room. Scheme of the system is shown in Fig. 3. Solar system consists of two glazed PVT collectors with gross area 3.42 m^2, storage water tank with volume 400 l, basic control components (circulation pump, closing and safety fittings, pressure and temperature sensors) and pipelines with thermal insulation. Heat transfer fluid was water. PVT collectors were installed on the metal construction of south orientation with tilt angle 45°. Solar system is dedicated to the preparation of domestic hot water in central storage tank but it does not fit to realistic design (high volume of the storage to collector area ratio). It was set up as laboratory system to provide the experimental testing of continuous PVT collectors operation under realistic climate conditions with dynamic behavior. Solar PVT collectors are directly connected to storage water volume, hot water is taken from integrated tube heat exchanger (similar to combined storage tanks). Conventional controller has been installed with the monitoring of the temperature difference and switching on and off the circulation pump of the system. Mass flow in the collector loop was set to 180 $l.h^{-1}$. Hot water load has been emulated by time-controlled electromagnetic valve representing the tapping device. Simple hot water load profile consisted from 4 loads with duration from 5 to 10 minutes was used at flowrate 5 $l.min^{-1}$. Daily hot water draw off was 200 l to provide sufficient load for the storage. Solar system works as solar only system for water preheating and auxiliary heater was not installed. For measurement was used pyranometer Kipp & Zonen (type CMP 6), wattmeter Hioki Power HiTester -3334, magnetic flowmeter TCM 142/02/3715, anemometer, and temperature sensors Pt100. For the electric part there is hybrid inverter INV (with MPP tracker), two batteries BATT (24 V x 140 Ah = 3360 Wh) and continuous electric load (see Fig. 3) for PV electricity. Energy from batteries was used continually in order to avoid full charged battery and reduction of useful PV electricity generation.

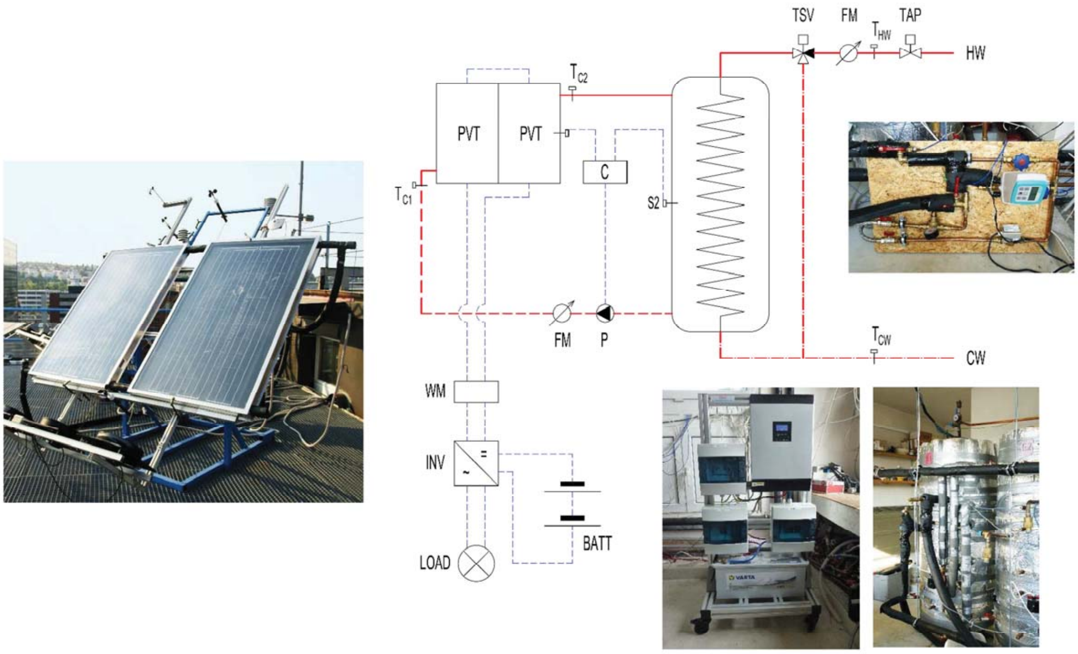

Fig. 3: Scheme of the solar DHW system with PVT collectors

5. Comparison between measured and simulated data

Thermal and electric output generated by solar PVT collector field has been evaluated for 6 days (from 18.5.2016 to 23.5.2016). Electric power, collector flowrate and temperatures at input and output of the collector field has been monitored in 30s time step together with climatic data (solar irradiance, ambient temperature, wind velocity). Electric power of PVT collectors was measured by digital wattmeter WM. Flowrate was measured by electromagnetic flowmeter FM and temperatures were monitored with Pt100 sensors.

Measured thermal and electric output data typical for clear and cloudy day is shown in Fig. 4 and Fig. 5. Heat output peaks are caused by switching the circulation pump on and off. For example at 9.00 am mean fluid temperature in the collector is higher compare to temperature in storage therefore pump is turned on. Although in short time temperature in collector is cooled because irradiation is not sufficient high, the same phenomena is during the evening. Fluctuation of thermal performance during the day is caused by cloudiness. These dynamic states are convenient for observation of the dynamic behavior and comparison with the steady state and dynamic model. During the clear day the heat output peaks are present only at morning and evening. Cloudy day leads to frequent heat output peaks during the whole daytime.

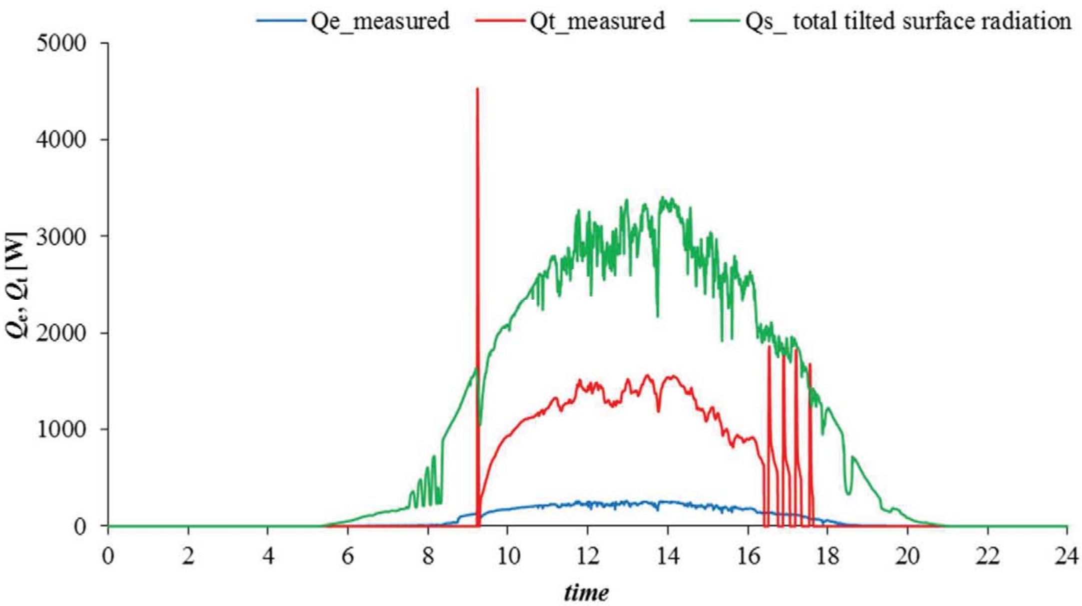

Fig. 4: Thermal and electric performance during clear day (22.5.2016)

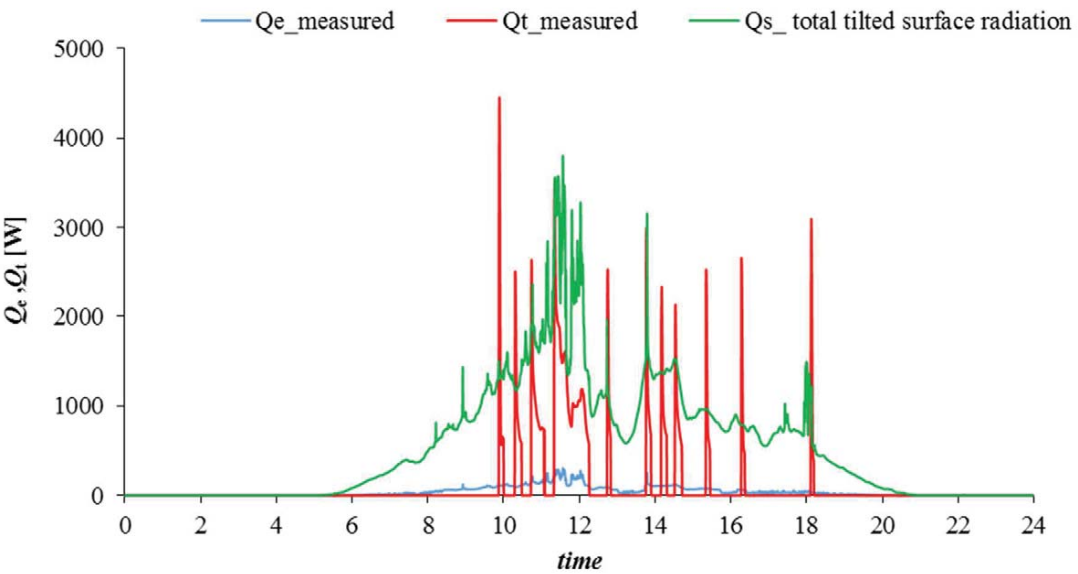

Fig. 5: Thermal and electric performance during cloudy day (18.5.2016)

Tab. 2: Measured data on the SDHW system with PVT collectors (for area 3.42 m^2)

Date	Incident solar irradiation Q_s [kWh]	Measured electric gain Q_e [kWh]	Electric efficiency η_e [%]	Measured heat gain Q_t [kWh]	Thermal efficiency η_t [%]
18. 5. 2016	12,8	0,91	7,1	2,93	22,9
19. 5. 2016	17,4	1,18	6,8	5,84	33,6
20. 5. 2016	16,6	1,17	7,0	4,98	29,9
21. 5. 2016	19,3	1,41	7,3	6,46	33,4
22. 5. 2016	24,3	1,76	7,2	9,05	37,2
23. 5. 2016	16,7	1,23	7,4	5,80	34,6

Tab. 2 shows the measured data from SDHW system. Daily thermal and electric gain was evaluated and daily efficiency of the collectors related to gross area has been determined. Tab. 3 shows the theoretically determined data by simulation model (steady-state, dynamic) and differences between modeled and measured values. Thermal energy difference for whole 6 days period of testing was -7 % for steady-state model and less than 1.5 % for dynamic model. Difference in modelled and measured electric energy was 8.1 % for the whole testing period. Maximum daily difference of the heat output are present during cloudy days but still less than 10 % for dynamic model, while quite large difference has been monitored for the steady-state model. Maximum difference between electric output modelled and measured is 15.7 %. This overestimation of electricity production by the model especially for cloudy days could be caused not only by quality of the model but also by operation out of the range of used hybrid inverter and power point tracker. This will be further investigated.

Tab. 3: Simulated daily energy output by model including difference from measured energy

Date	$Q_{e,stac}$ [kWh]	$\Delta_{e,stac}$	$Q_{t,stac}$ [kWh]	$\Delta_{t,stac}$	$Q_{t,dyn}$ [kWh]	$\Delta_{t,dyn}$
18. 5. 2016	1,02	12,3 %	1,83	-37,5 %	3,17	8,5 %
19. 5. 2016	1,37	15,9 %	5,60	-4,2 %	5,93	1,5 %
20. 5. 2016	1,30	11,0 %	4,22	-15,2 %	5,21	4.7 %
21. 5. 2016	1,48	5,6 %	5,95	-7,8 %	6,36	-1,5 %
22. 5. 2016	1,83	3,8 %	9,20	-1,6 %	9,03	0,2 %
23. 5. 2016	1,28	3,7 %	5,83	0,7 %	5,76	-0,5 %

Fig. 6 shows a detailed comparison between measured and modeled data for part of the clear day. To show the difference the steady-state and dynamic modeled data are put together with measured data in the graph. Dynamic model corresponds to measured data quite well in the whole period including the heat output peaks at the end of the day. Heat gain modelled with steady-state model without PVT collector capacity term oscillates during the operation and this results in worse precision of the model when compared to measured data.

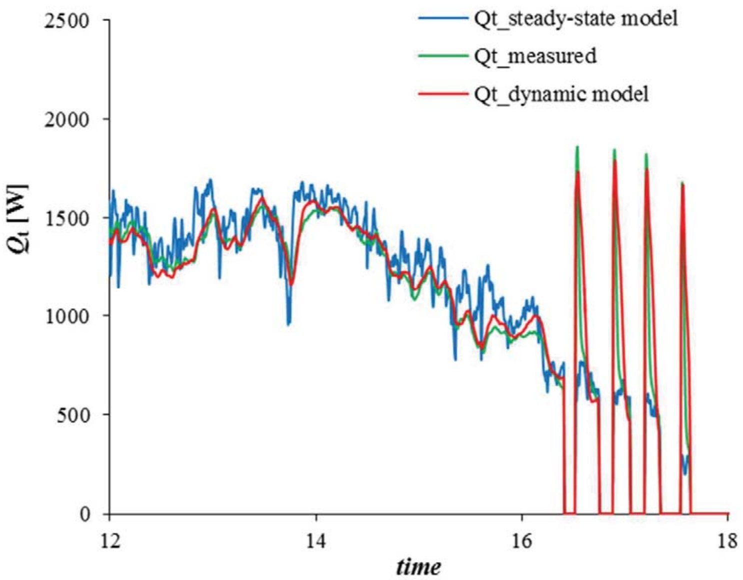

Fig. 6: Comparison between measured and modelled thermal performance (22.5.2016)

Fig. 7 shows the comparison of measured and modeled electric output. Significant differences of electric output are obvious particularly during the morning and evening. One possible reason of discrepancy is that hybrid inverter works out of his range as mentioned above. Due to this fact measured electric output is lower than modeled electric output. However the electric model could be improved further. Currently, the electric model does not consider non-uniform temperature distribution across the collector plane. Temperature difference between the area close to inlet and the area close to outlet can be more than 5 K.

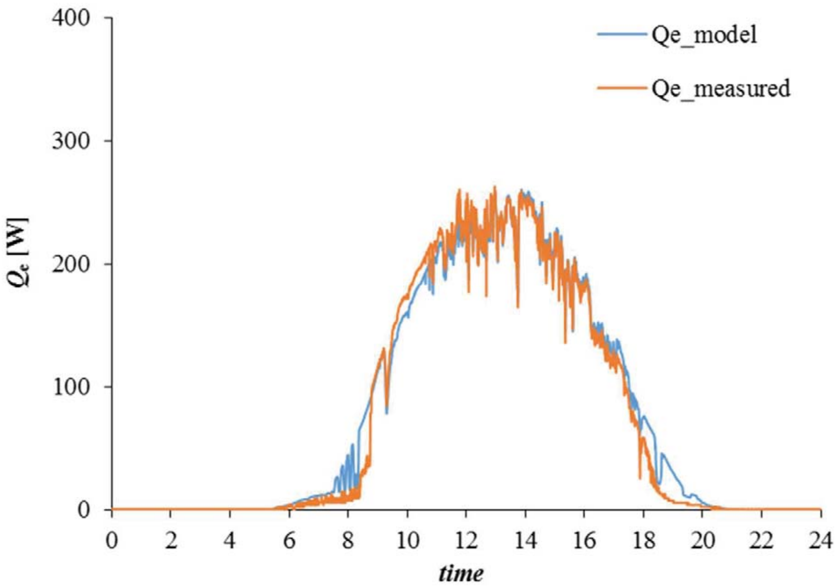

Fig. 7: Comparison between measured and modelled electric performance (22.5.2016)

6. Conclusion

The detailed mathematical model of new concept of glazed PVT collector has been validated by steady-state testing and further extended to dynamic model. The prototypes of the developed glazed PVT collectors has been fabricated and used in laboratory system for domestic hot water preparation. The performance PVT collectors in the system has been monitored and results have been compared with a simulation using the developed dynamic model implemented into TRNSYS. The comparison has shown a good agreement for the thermal part of the model (compared to steady-state model) and relatively good agreement with electrical part during the sunny days.

Main findings

- Prototype of PVT collector with durable lamination over high operating temperatures
- Dynamic model of PVT collector implemented into the TRNSYS as a new type

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