EXPERIMENTAL INVESTIGATION OF SOLAR PV-T/LIQUID COLLECTOR

Tomáš Matuška, Luboš Buchta

Faculty of Mechanical Engineering, Czech Technical University in Prague (Czech Republic)

1. Introduction

Integration of photovoltaic and thermal liquid collector into one component brings several advantages for solar applications. Hybrid concept of unglazed photovoltaic-thermal (PV-T) collector with combined heat and power production allows an effective use of solar energy incident on building envelope area if low temperature heat is used in suitable technical systems of building. Moreover, building envelope integrated PV modules need cooling not only to increase the electricity production but also to protect the PV cells against degradation by excess thermal load and to maintain their standard life-time.

Unglazed type of PV-T collectors is suitable to applications with priority of electricity generation (increase of yield by cooling) and waste heat removed from cells is a by-product at low temperature level with worse usability than in standard solar thermal collectors. Compared to glazed PV-T collectors with higher available temperatures unglazed alternative represents robust and simple construction with reduced risk of damage due to overheating at stagnation conditions without heat removal.

PV-T collectors cooled by a liquid have crucial advantages compared to air PV-T collectors, especially in low parasitic electric energy need for system thanks to high thermal capacity of fluids, easy building envelope integration because of small dimensions of distribution system and good usability of heat in summer e.g. for cold water preheating or primary circuits of heat pumps (Charalambous, 2007).

Commercial production of economically viable PV-T collectors is still on starting point. Requirement of integration of two completely different technologies into one product makes the PV-T collectors expensive. Costs of commercial unglazed PV-T collectors (450 to 550 EUR/m^2) are still usually two times higher compared to PV modules (200 to 250 EUR/m^2). On the other side, unglazed PV-T collectors are a suitable concept for low-cost production from standardized commercial components - PV module and thermal absorber (heat exchanger) joined together by an adhesive bond. However, simplicity of such low-cost production is balanced by generally lower thermal performance (Zondag, 2004), especially due to:

- high thermal resistance between liquid and PV cell (laminate layers, adhesive bond, irregularities in flatness of absorber, possible air traps or dry contacts, heat exchanger configuration);
- white gaps between PV cells in commercial PV modules because of white foils used for back side encapsulation; this results in reduced absorption of solar radiation at aperture area.

Experimental investigations presented in the paper have been carried out with low-cost PV-T collectors prepared from commercial PV modules with heat exchangers (those typically used in solar thermal collectors) with different type of contact between them. Main purpose of the work was to investigate the influence of different configuration of heat exchanger (pipe structure, plate/pipe structure) and contact (ůdry" contact, standard epoxy resin, epoxy resin filled with aluminium particles) on thermal performance and influence of thermal insulation used at back side (case of building envelope integration). Based on experimental results a previously developed mathematical model PVT_NEZ (Matuska, 2010) has been improved and verified to allow further investigation on potential of low-cost PV-T collectors especially for building integrated applications.

2. Investigated unglazed PV-T collector alternatives

Investigated concept of unglazed PV-T liquid collector uses a heat exchanger (absorber) attached to back side of the commercial PV module for cooling by liquid (water, antifreeze mixture), eventually equipped with thermal insulation layer. The concept can be applied both for low-cost production of new unglazed PV-T collectors and for retrofit the already installed PV modules.

PV-T collectors are based on polycrystalline silicon PV module with peak power 210 W_p. Gross dimensions of PV module are 1500 x 990 mm and aperture area is 1.485 m^2. Total 54 polycrystalline photovoltaic cells are laminated between glass/EVA foil (front) and PET foil (back). PV laminate is integrated into aluminium frame.

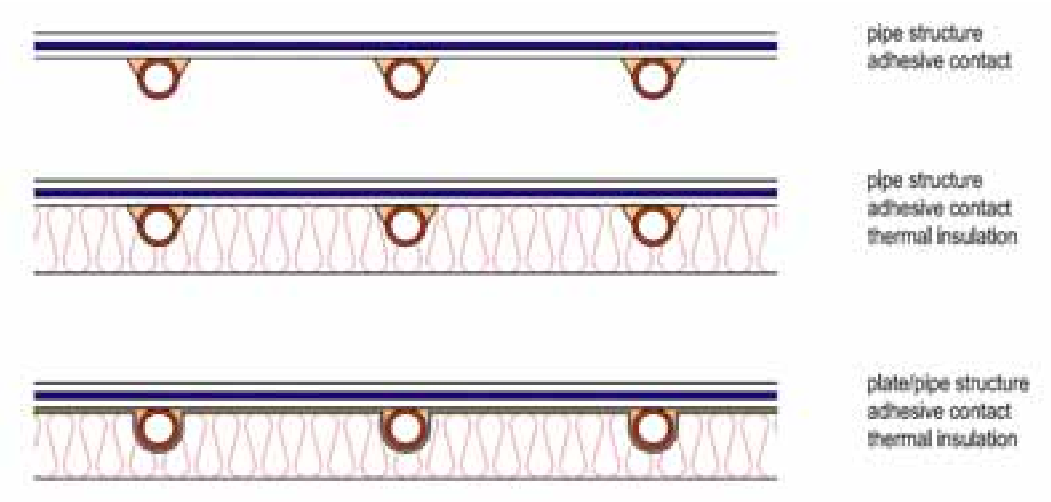

Fig. 1: Configurations of bond between pipe heat exchanger and PV module

Several alternatives of PV-T collector design have been prepared (see Fig. 1), two types of heat exchanger combined with different thermal quality of contact with PV laminate (dry, adhesive resins) and eventually thermal insulation. Heat exchanger alternatives for liquid cooling of PV module are of common design for solar thermal collectors: copper headers (22 x 1 mm) and risers (10 x 1 mm) in harp configuration. Distance between two adjacent pipes is 100 mm. One alternative use only copper pipes structure with no heat conducting fins (see Fig. 2), second one is a structure with identical layout but with aluminium plate (absorber) of thickness 0.3 mm forced on pipes (see Fig. 3). Three different thermal contacts have been used: "dry" contact without glue or paste, standard epoxy resin (CHS EPOXY 531/TELALIT 0492, further "epoxy") and epoxy resin filled with aluminium powder (volume concentration of aluminium 1:25, further "epoxy-AL").

Several specimens were prepared with thermal insulation (extruded polystyrene) of thickness 40 mm, integrated into original aluminium frame of PV module (see Fig. 2 and Fig. 3).

Fig. 2: Pipe heat exchanger glued to PV module without insulation (epoxy, epoxy-AL) and with insulation (epoxy)

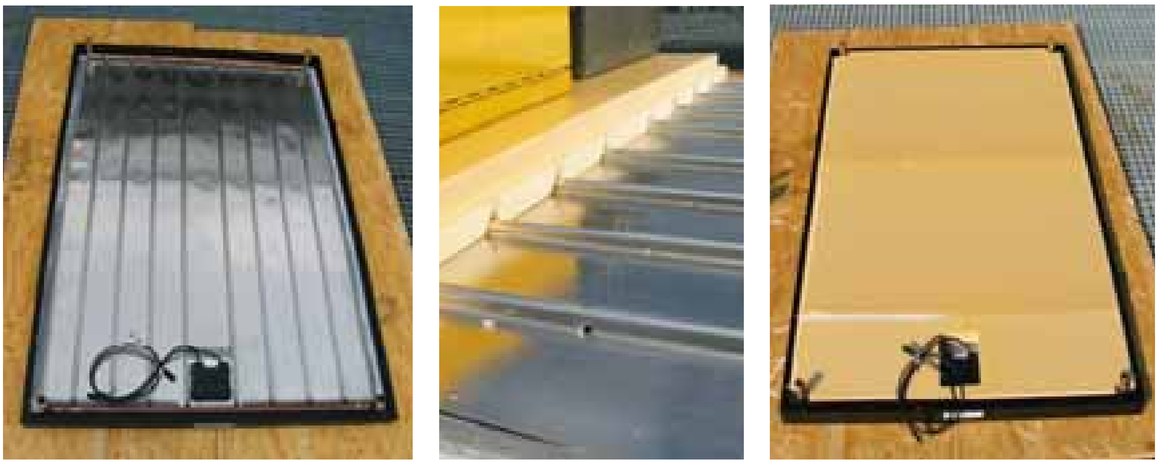

Fig. 3: Plate/pipe heat exchanger glued to PV module without insulation and with insulation (detail, covered)

3. Experimental work and results

Proposed alternatives of unglazed PV-T collectors have been experimentally studied at Solar laboratory at CTU in Prague. Thermal performance of PV-T collectors has been evaluated to investigate the influence of both thermal contact heat exchanger/laminate and thermal insulation applied on effectiveness of PV laminate cooling. Method for unglazed collectors in accordance with EN 12975-2 for outdoor steady-state conditions has been used with no electricity load applied. Measured values for conditions of wind velocity under 1 m/s have been taken for thermal efficiency evaluation. Fig. 4 shows PV-T collectors at test stands in Solar laboratory.

Fig. 4: Investigated unglazed PV-T collectors at test stand

Fig. 5 (left) shows efficiency curves for PV-T collector with pipe structure as heat exchanger glued to back side of PV laminate with two different epoxy resins and no thermal insulation applied. Heat transfer from PV cell to liquid is dramatically reduced by low conductivity of laminate together with large spacing of pipes (100 mm). This results to low value of zero-loss efficiency under 30 % for both alternatives. Better thermal conductivity of epoxy resins with aluminium powder (epoxy-AL) increases the efficiency to certain extent but influence of low conduction through laminate material is prevailing for total heat transfer.

Fig. 5 (right) shows comparison of PV-T collectors with pipe structure glued by standard epoxy resin in alternatives without and with thermal insulation layer applied to back side (to simulate building envelope integration). Despite the poor thermal quality of laminate-pipe contact, the application of thermal insulation significantly increases the effectiveness of heat removal from PV laminate due to considerably lower back heat loss.

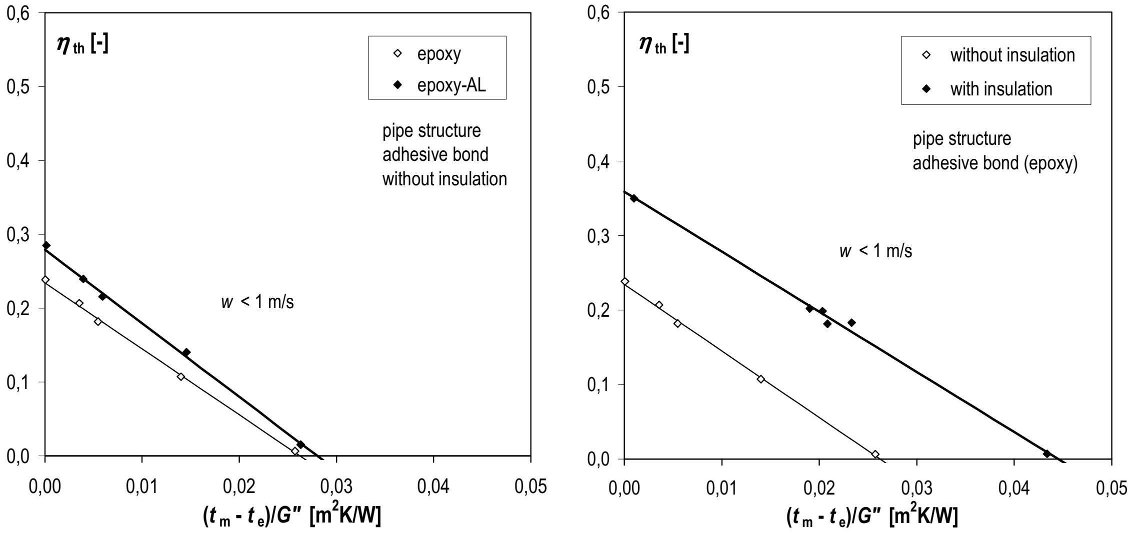

Fig. 5: Results for PV-T collector with pipe heat exchanger

Fig. 6 (left) shows a comparison of efficiency curves for PV-T collectors with plate/pipe heat exchanger attached to PV laminate by "dry" contact and glued by two resins (epoxy, epoxy-AL). All alternatives have a thermal insulation 40 mm applied to back side. Better heat removal from back side of PV laminate by a plate/pipe heat exchanger results in significantly increased efficiency compared to simple pipe structure. Thermal quality of bonding material has a minor importance, even the "dry" contact shows a considerable improvement compared to glued pipe structure.

Fig. 6 (right) gives an indication on thermal power useable at different temperature levels (for $G" = 1000\ W/m^2$). Peak thermal power is 3 to 4 times higher than peak electric power of PV module for investigated alternatives with plate/pipe heat exchanger.

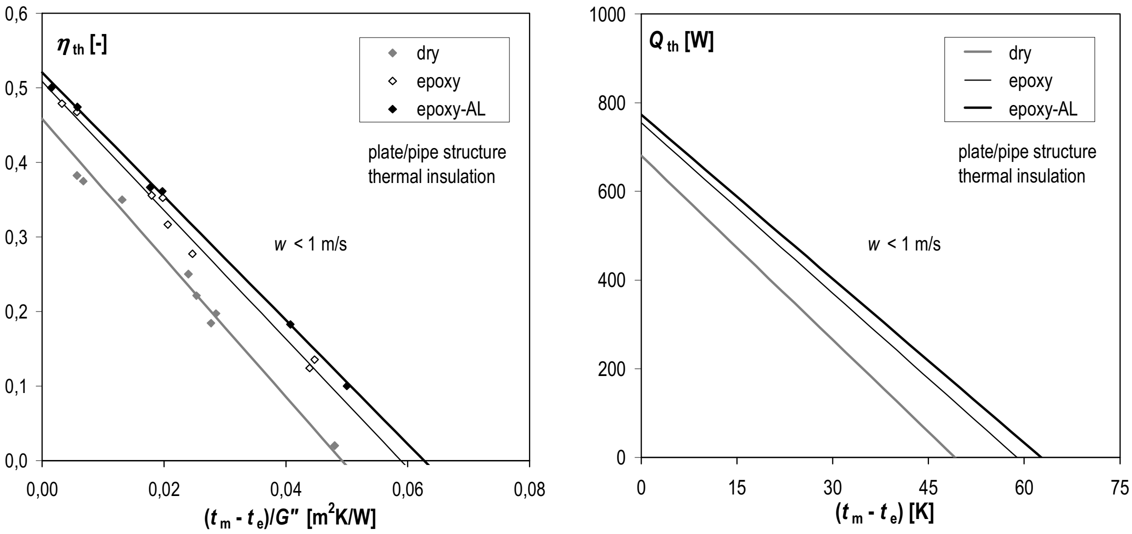

Fig. 6: Results for PV-T collector with plate/pipe heat exchanger with thermal insulation

4. Theoretical modelling

A detailed mathematical model of unglazed solar flat-plate hybrid PV-T liquid collector (PVT-NEZ) has been developed previously (Matuska, 2010). Model is based on theory for energy balance of solar thermal collectors (Duffie and Beckman, 2006) expanded for photovoltaic conversion (Florschuetz, 1979). Input parameters of the model are thermal, optical, electrical and geometrical properties of individual parts of PV-T collector (e.g. PV reference electric efficiency, temperature coefficient; material and geometry for heat exchanger, thermal insulation layer if applied), climate conditions (solar irradiance, ambient temperature, wind velocity, sky emissivity) and operation conditions (temperature of fluid entering collector, mass flow rate). Output parameters of the model are usable electric power and thermal power.

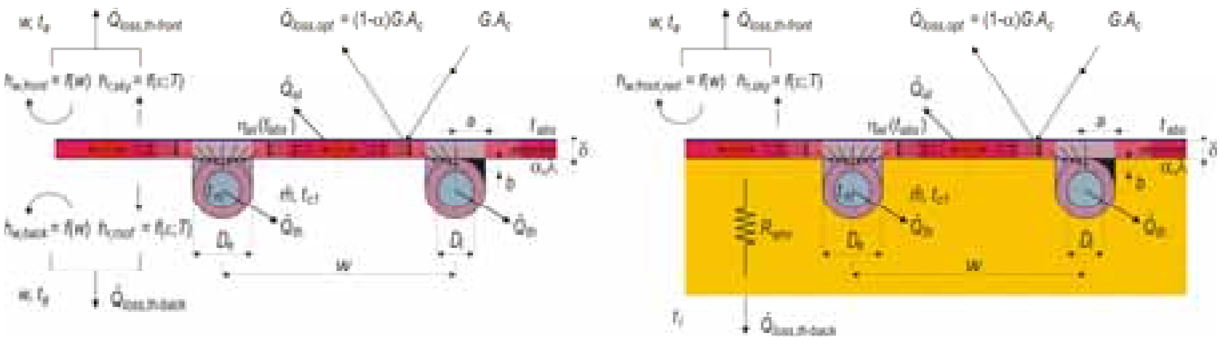

Fig. 7: Scheme of unglazed PVT-NEZ model (standalone, building envelope integrated alternative).

Mathematical model PVT-NEZ consists of 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. 7. Mathematical model PVT-NEZ has been subjected to verification by experimental data for investigated low-cost PV-T collectors with back thermal insulation (building integration case). For given PV-T collectors configurations and parameters (glued pipe heat exchanger, glued plate/pipe heat exchanger), thermal output has been theoretically modelled for identical boundary conditions as for experiments and results were compared.

Principle uncertainty of PV-T collector model is generally associated with theoretical definition of unknown thermal bond conductance. Is has been assumed a value 3 W/(m.K) for bonds with standard epoxy resin and 4 W/(m.K) for epoxy-AL bond. Thermal conductivity of aluminium plate (0.3 mm) has been considered 240 W/(m.K), thermal conductivity 1.2 W/(m.K) for back side laminate of PV cell (3 mm) has been used and a value 0.032 W/(m.K) for thermal insulation from extruded polystyrene (40 mm).

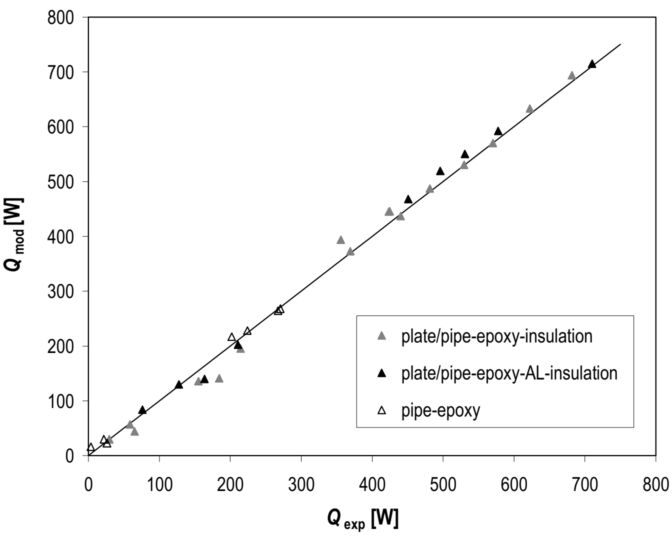

Fig. 8: Verification of mathematical model with experimental data for three alternatives of PV-T collectors

Second important source of uncertainty for modelling unglazed solar collectors generally is a wind convection calculation (Sartori, 2006). Robust model derived from (Test et al., 1981) has been chosen as suitable for different wind velocities in calculation process. However, reliable wind convection model still remains a crucial problem in theoretical modelling of unglazed collectors.

Experimentally derived values of thermal output of PV-T collectors which have met a requirement of stationary conditions (for different climatic and operation conditions) have been compared with modelled results for identical boundary conditions (solar irradiance, ambient temperature, wind velocity, sky emissivity, mass flow rate, input fluid temperature, no electric load applied). Results for three alternatives are shown in Fig. 8. Although the values are subject of uncertainty of both experimental testing and quality of model input parameters, the graph shows a relatively good agreement between experiment and model.

5. Conclusions

Experimental investigation of low-cost unglazed PV-T collector prepared from commercially available components has been performed at outdoor conditions according to EN 12975. Alternatives based on PV module with glued pipe structure resulted in very poor thermal performance. As promising improvement could be seen an integration into building envelope (here substituted by thermal insulation of 40 mm) which significantly increase the thermal performance and effectiveness of PV module cooling, both for simple pipe structure and for plate/pipe heat exchanger.

A verification of previously developed mathematical model for unglazed PV-T collector has been done for alternatives with thermal insulation applied to back side and good agreement has been shown between theoretically and experimentally derived thermal output data. The most uncertain part of model verification is wind convection and it should be further studied. Future work will be focused on modeling and experimental investigations of PV-T electric performance.

6. References

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

Zondag, H. A. et al., 2004. PV-Thermal collector development – an overview of the lessons learnt. 19th PV Solar Energy Conference and Exhibition, 2004, Paris (France).

Matuska, T., 2010. Theoretical Analysis of Solar Unglazed Hybrid Photovoltaic-Thermal Liquid Collector, in: Proceedings of Eurosun 2010, Graz (Austria), ISBN 978-3-901425-13-4.

Duffie, J. A., Beckman, W.A., 2006. Solar enginnering of thermal processes. 3rd edition. Wiley 2006, ISBN 13-978-0-471-69867-8.

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

Sartori, E., 2006. Convection coefficient equations for forced air flow over flat surfaces. Solar Energy 80 pp. 1063–1071.

Test, F.L., Lessmann, R.C., Johary, A., 1981. Heat transfer during wind flow over rectangular bodies in the natural environment. ASME J. Heat Transfer 103, 262–267.