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Performance and heat transfer analysis of uncovered photovoltaic-thermal collectors with detachable compound

Steffen Brötje*, Maik Kirchner, Federico Giovannetti

Institut für Solarenergieforschung Hameln GmbH (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany

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A B S T R A C T

Concerning the manufacturing of uncovered, liquid-based photovoltaic-thermal (PVT) collectors, design requirements or low expenses have higher priority than the all-out optimization of the thermal efficiency. The specific impact of inevitable thermal resistances caused by wavy surfaces and imperfect contacts between PV modules and heat exchangers has not been comprehensively investigated yet. This paper focuses on the performances of uncovered PVT collectors with detachable mounting of PV modules on heat exchangers and the effect of macroscopic air gaps. Two prototypes with thin film modules were built without using silicon glue, other adhesives or heat conductive paste. Measured in sun simulator in electrical open-circuit mode, the thermal zero-loss efficiencies for the adhesive-free collectors are $\eta_{0,M}$ = 66.8% (copper pipe meander laser-welded on aluminium sheet) and $\eta_{0,M}$ = 69.2 % (aluminium roll-bond) based on gross areas. These results are similar or better than the efficiencies of commercially available collectors. Due to the thermal resistance of air gaps, we calculated temperature differences of 12 K and higher between absorbing sheets and heat carrier, which have to be considered while estimating the electrical yield by means of system simulations. For comparison, we built a prototype with a roll-bond heat exchanger and a very thin adhesive layer and thereby an optimized heat transport ($\eta_{0,M}$ = 76.8 %). Using numerical, two-dimensional models, we can verify the efficiency measurements and determine the influence of design and boundary conditions on heat transfer mechanisms in the collectors. Simulations show good agreement with experimental results and prove to be an effective tool for design optimization.

1. Introduction

Liquid-based photovoltaic-thermal collectors (PVT) are often built with adhesives to get a non-detachable compound, and thus a more efficient thermal coupling of photovoltaic (PV) module and heat exchanger. The compound design is crucial for the transport of the (mostly in the PV cells) absorbed heat into the fluid. Nevertheless, the adhesive connection also leads to disadvantages, such as high requirements for materials and manufacturing and, therefore, to high costs. A glue-free and detachable compound – with frictional or form-closed connection – may offer the possibilities to save material and expenses, replace damaged PV-modules and reduce thermal-mechanical stresses. By contrast, the internal heat transfer coefficient may decrease due to the waviness of the surfaces and the resulting suboptimal thermal contact, as outlined in Fig. 1. Dirt and moisture may penetrate into the air gap and additional mechanical reinforcements (rear profile, plates, etc.) may be necessary to ensure adequate thermal coupling and performance.

On the market of liquid-based PVT collectors there are various products, which are very different in their construction. The most obvious differences are the type and material of heat exchanger and the utilization – or non-utilization – of adhesives, as listed in Table 1. Those differences account for a wide distribution of thermal performances. The reported technical data refers to Solar Keymark test results and manufacturer specifications. Especially those products that do not have any glued connection (e.g. by adhesive, tape) between PV panel and heat exchanger show a wide range of thermal efficiency. Additional information about test methods and results of those collectors is given in Tables 9 and 10 (appendix). It should be noted that the majority of power measurements was performed at the maximum electrical output (Maximum Power Point, MPP) and that the efficiency results at MPP are not comparable to open-circuit tests (OC, no current). For the considered products, an approximate comparison is possible by assuming typical electrical efficiencies of the corresponding PV panels (c-Si).

Despite the growing PVT-market, according to the author's knowledge the heat transfer mechanisms and the potential of glue-free solutions have not yet been analysed in detail. Several comprehensive reviews investigate the design and performance of uncovered (WISC) PVT

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* Corresponding author.
E-mail address: broetje@isfh.de (S. Brötje).

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Nomenclature

A_{coll}	PVT collector gross area
a_1	heat loss coefficient (glazed collector) at $T_{f,m}$-T_a = 0 (W/(m^2 K))
a_2	temperature dependence of the heat loss coefficient (glazed collector) (W/(m^2 K^2))
b_1	heat loss coefficient (uncovered collector) at $T_{f,m}$-T_a = 0 (W/(m^2 K))
b_2	wind dependence of the heat loss coefficient (uncovered collector) (W s/(m^3 K))
b_u	collector efficiency coefficient (wind dependence) (uncovered collector) (s/m)
c_1	heat loss coefficient (quasi dynamic model) at $T_{f,m}$-T_a = 0 (W/(m^2 K))
c_2	temperature dependence of the heat loss coefficient (quasi dynamic model) (W/(m^2 K^2))
c_3	wind speed dependence of the heat loss coefficient (quasi dynamic model) (J/(m^3 K))
c_4	sky temperature dependence of the heat loss coefficient (quasi dynamic model)
c_6	wind dependence in the zero loss efficiency (quasi dynamic model) (s/m)
c_p	specific heat capacity of heat carrier (J/kg K)
G''	net irradiance (W/m^2)
G	hemispherical solar irradiance (quasi dynamic model) (W/m^2)
HX	heat exchanger
h_{fluid}	heat transfer coefficient in fluid channel, from wall to fluid (W/(m^2 K))
$K_{\theta 50}$	incidence angle modifier (50°)
K_d	incidence angle modifier for diffuse radiation
K_{el}	angle correction factor for the spectral selectivity of the electrically active PV module
K_{th}	angle correction factor for the thermal absorption of the collector
$P_{el,rel}$	relative electric power compared to MPP (Maximum Power Point), 0 < $P_{el,rel}$ < 1
$\dot{Q}_{use}$	useful heat flow (W)
Re_m	average Reynolds number
R_{th}	thermal resistance (W/(m^2 K))
s_{eq}	thickness of air layer equivalent (mm)
T_a	ambient temperature (°C)
$T_{Cell,m}$	determined cell temperatures acc. to eq. (11) (°C)
$T_{f,m}$	mean fluid (heat carrier) temperature (°C)
u	wind speed (m/s) T_a
U_{int}	internal heat transfer coefficient between solar cells and heat carrier (W/(m^2 K))
WISC	acronym: wind and infrared sensitive collectors (ISO 9806:2016)
Y	temperature power coefficient of the PV module (%/100)
α_{eff}	effective thermal absorption coefficient of the PV module (measured)
α_{th}	coefficient of thermal expansion (1/K)
$\eta_{0,i}$	conversion factor (thermal efficiency at $T_{f,m}-T_a = 0$)
(Index M: measured; S: Simulated)	
$\eta_{PV,max}$	electrical efficiency of the PV module under standard test conditions (STC)
λ	thermal conductivity (W/(m K))

collectors based on different PV cell technologies and heat exchangers (Aste et al., 2017; Brahim and Jemni, 2017; Chow, 2010; Hasan et al., 2017; Ibrahim et al., 2011; Zondag, 2008). Some take into account the hydraulics and fluid mechanics, the majority is about both covered and uncovered PVT. Although the heat transfer from absorbing material to heat carrier is discussed and the gap between PV cells and heat exchanger (absorber) is determined as crucial, those publications are not evaluating the quantitative impact of the connection between PV module and heat exchanger including macroscopic or microscopic air gaps. Other works feature collectors with clamped and glued compounds and compare their efficiencies (de Keizer et al., 2016; Herrando et al., 2014).

This publication focuses on the clamped type of hybrid collectors, in particular on collectors without rear insulation, which maximize the use of ambient heat and allow a simple construction with low material usage.

To evaluate the potential of non-glued compounds, especially for the use in uncovered PVT collectors for low-temperature applications, we manufactured simple prototypes by combining different commercially available heat exchangers and PV modules. Detailed experimental investigations on these customized hybrid modules and simulations based on the finite element method (FEM) were carried out to analyze the thermal performance and the usability of each concept. The investigations are targeting the thermal resistances of the air gap, which can occur due to the waviness of the PV-module or heat exchanger, as well as secondary issues like the influence of mass flow rate.

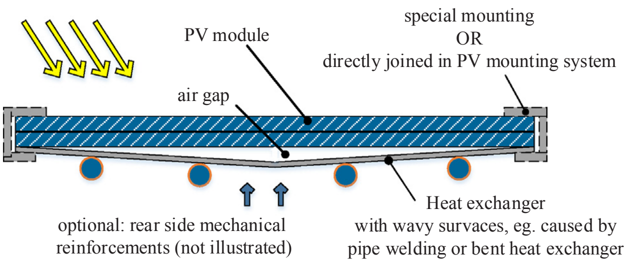

Fig. 1. Schematic, exemplary representation of a solar hybrid collector with adhesive-free connection and suboptimal thermal contact due to the air gap between PV module and heat exchanger.

2. Overview of methodology

In the following simulations, we both compare the internal heat transfer coefficient U_{int} and the thermal efficiency with experimental results. Fig. 2 gives an overview of the basic methodology used for the investigations. Additional ongoing methods at ISFH regarding the modelling of boundary conditions and heat losses are shown as well.

Supporting the detailed descriptions in the following sections, the marked sections ①–③ of Fig. 2 shall be explained beforehand:

① Internal thermal conductivity: The collector coefficients of uncovered thermal collectors are determined by means of indoor (in this publication) or outdoor measurements according to ISO 9806:2013 (ISO, 2013). The internal heat transfer coefficient U_{int} between the radiation-absorbing photovoltaic cells and the heat transfer fluid is calculated both on the basis of these collector coefficients and with the help of numerical simulations. The results can be compared directly. To evaluate and compare the results we introduce an equivalent air gap s_{eq}, which represents the thermal resistance of the existing gap between PV module and heat exchanger and is assumed as unknown quantity in the calculation. Using this method, we can evaluate the mechanical compound by means of thermal contact and decide whether to optimize the design and repeat the test.

② Efficiencies/thermal performance: The measurements and resulting collector coefficients give information about the performance under different ambient weather conditions (not including condensation, rain