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Author(s):
Hischier, Illias; Hofer, Johannes; Gunz, Lukas; Nordborg, Henrik; Schlueter, Arno

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Integration of Renewable Energy in the Built Environment (Electricity, Heating and Cooling)

Ultra-thin and lightweight photovoltaic/thermal collectors for building integration

Illias Hischier[a,*], Johannes Hofer[a], Lukas Gunz[b], Henrik Nordborg[b], Arno Schlüter[a]

[a]*Chair of Architecture and Buildings Systems, ITA, ETH Zürich, Switzerland*
[a]*Institute for Energy Technology, IET, HSR Hochschule für Technik Rapperswil, Switzerland*

Abstract

Unglazed PVT collector concepts to cover electricity and heat demands of LowEx Buildings have been experimentally and numerically evaluated. Critical aspects affecting electrical and thermal efficiency are identified. A promising solution was found in the direct lamination of thin-film solar cells onto a channel-plate thermal collector resulting in a highly efficient, super-light (<4kg/m^2) and ultra-thin (<4mm) PVT collector. The lightweight design simplifies building integration and reduces the amount of materials and associated costs as well as environmental impacts.

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Keywords: hybrid collector; unglazed; building integration; solar thermal; photovoltaic; LowEx

1. Introduction

Integrating solar thermal collectors and photovoltaic modules into the building envelope plays a key role for the contemporary goal of constructing net-zero and plus-energy buildings [1]. To maximize the energy harvest, photovoltaic/thermal hybrid (PVT) collectors have been proposed. In a PVT collector, the solar cells serve as the

* Corresponding author. Tel.: +41 44 633 75 15.
E-mail address: illias.hischier@arch.ethz.ch

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absorber to capture the incident solar radiation. Part of the radiation (typically 10-20%) is converted to electricity while the remainder is converted to useful heat in an adjacent thermal collector. A PVT collector hence not only is able to provide heat for building systems but simultaneously – by lowering the solar cell temperature – improves the electricity yield of the solar cells. Depending on application (e.g. air/water pre-heating, hot water for domestic/industrial use, etc.) and location-dependent conditions (e.g. climate and orientation), a variety of PVT collector concepts have been proposed in the past [2-4]. The various concepts have been classified in terms of design (e.g. glazing, concentration, degree of integration), type of heat removal (natural/forced fluid/gas flow, evaporative collectors, etc.) and type of solar cell (e.g. monocrystalline/polycrystalline silicon, thin-film solar cells, etc.) resulting in a variety of PVT class definitions such as liquid/air PVT, covered/uncovered PVT or concentrating PVT. More recently, the level of thermal insulation has been proposed as an alternative classification [5]. Generally, improved insulation (e.g. side and rear insulation and additional transparent cover) correlates with increased stagnation temperatures and increases challenges related to temperature resistance of materials, long-term degradation, thermal expansion, overheating protection, etc.

Most PVT collectors are based on a typical glazed flat plate collector design, i.e. a rectangular rear- and side-insulated box of about $2m^2$ with a glass cover [6]. From a buildings' perspective, the collectors are rather heavy, thick and available only in standard dimensions which limits the number of areas suitable for installation and confines architectural integration quality [7]. Moreover, they are typically optimized for operating temperatures of >50°C and not necessarily for the seasonally changing energy needs of buildings. For example in the LowEx Building concept – a promising approach for zero emission buildings – moderate supply temperatures are targeted to exploit valuable anergy sources. An example for such a system is the combination of thermally activated building systems (TABS) for low temperature space heating, an efficient heat pump, a borehole thermal storage and solar collectors supplying heat at moderate temperatures around 20-35°C [8]. These low temperatures can efficiently be provided with unglazed collectors e.g. low-cost plastic or channel-plate thermal collectors typically found in pool heating applications [9]. Unglazed solar thermal collectors are simple in construction, cheap and characterized by high heat exchange rates with the ambience and consequently low stagnation temperatures. These properties make unglazed collectors ideal candidates for low-temperature PVT collectors e.g. in conjunction with thin-film solar cell laminates.

In the present study we focus on "unglazed" PVT collectors, i.e. built entirely without glass. Instead, thin-film solar cells encapsulated between thin plastic sheets are used. This results in a significant weight reduction compared to glazed PVT collectors where solar cells – typically crystalline silicon – are imbedded in between two glass layers and/or protected by a glass cover. In addition, to further reduce the weight and thickness, a thermal collector based on rollbond or extrusion techniques is envisaged. The resulting light and thin PVT collector is expected to facilitate installation and improve architectural integration quality.

2. Experimental analyses

To identify critical aspects affecting thermal and electrical performance as well as architectural integrability, two different PVT collector designs, named "channel-plate" and "tube-foil" are studied in detail. The designs are based on flexible 3mm thick CIGS solar modules glued onto (1) a 0.4m wide, 1.8m long and 3mm thick channel-plate collector made from multiport extrusion (MPE) aluminum microchannel profiles with a total of 108 parallel channels; and (2) a 0.6m wide, 2m long and 3mm thick tube-foil collector made from a polypropylene capillary mat with 54 parallel tubes and covered by a thin aluminum foil (Fig. 1). The header tubes, which supply the thermal collector channels/tubes with water, increase the overall thickness to ~20mm at the inlets and outlets of the thermal collector.

The prototypes were installed on a tilted, insulated wooden frame simulating roof or façade integration into a building (Fig. 2). Experimental tests were conducted outdoors, under sunny conditions in Zurich, Switzerland in winter time. A commercial water chiller system was used to supply the PVT collector with water at a constant temperature. Temperature increase across the collector was measured by Pt100 sensors installed at the collector water inlet and outlet, respectively. Water mass flow was manually adjusted and measured with a magnetic flow meter. Irradiance and wind speed were measured by pyranometer and anemometer, respectively. Additionally, surface temperature distributions were measured by IR thermography.

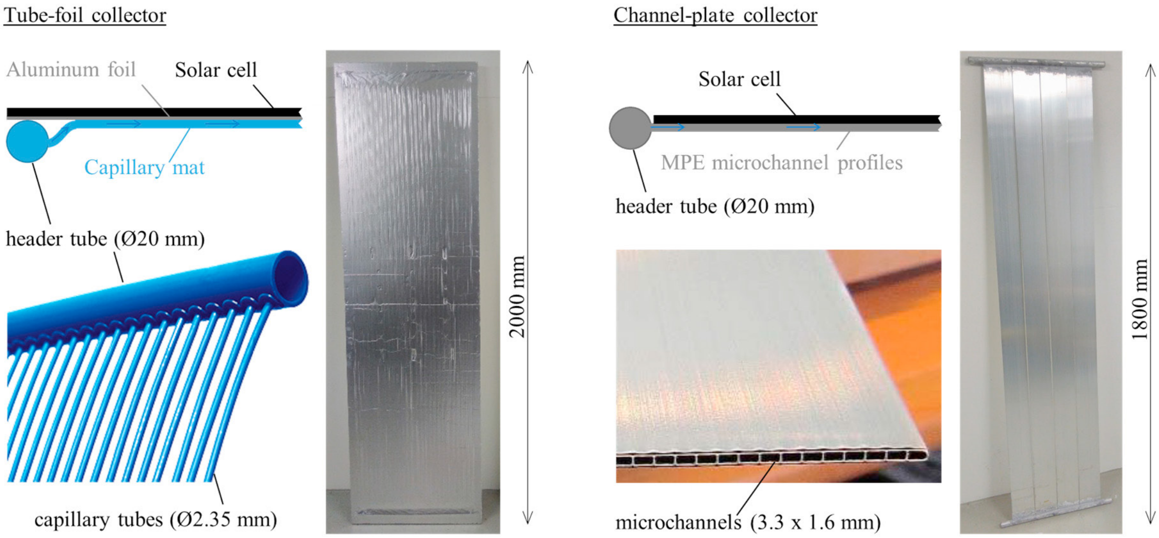

Fig. 1. Schematic representations and photographies of tube-foil (left) and channel-plate (right) collector prototypes (without PV).

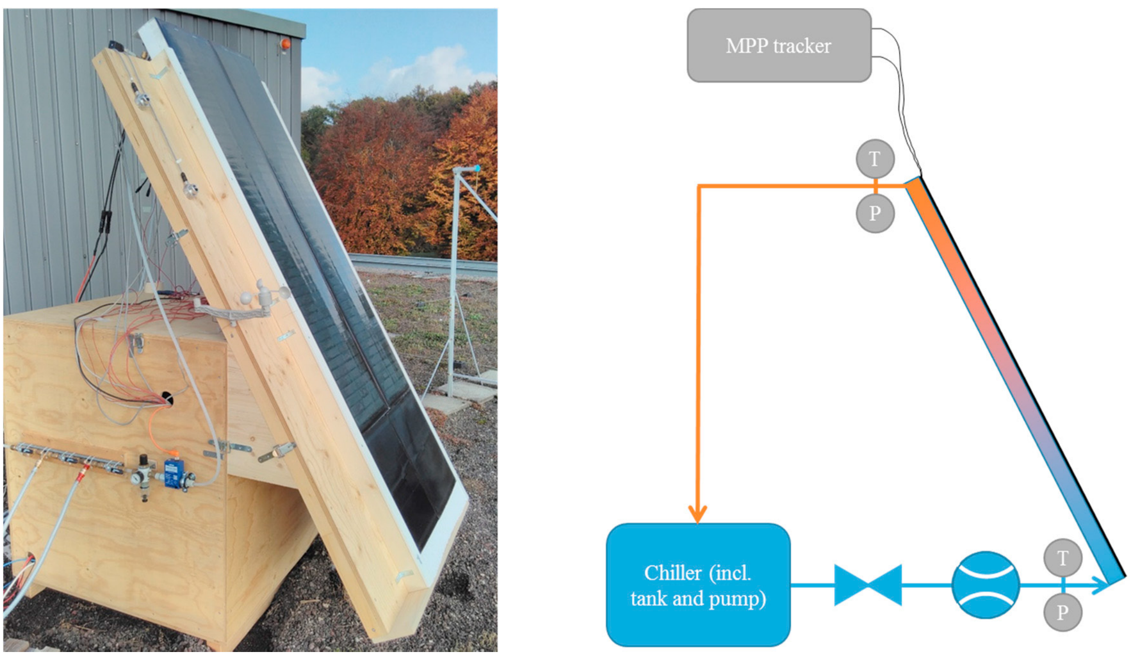

Fig. 2. Photography and schematic representation of experimental setup used to evaluate the PVT prototype concepts under outdoor conditions. P and T represent location of pressure and temperature measurements.

Fig. 3 shows the experimentally measured thermal efficiency of the channel-plate and tube-foil designs along with the IR measured surface temperature distributions. Measurements were taken at steady state conditions, and wind speeds and irradiance of <1 m/s and > 600W/m^2, respectively. The solar modules were operated in open circuit mode, i.e. no electricity was generated. Each data point represents an averaged value of 50 measurements taken over a time period of 2.5 minutes. Error bars indicate 95% confidence interval of cumulated instrument errors (bias) and variations in the measured data set.

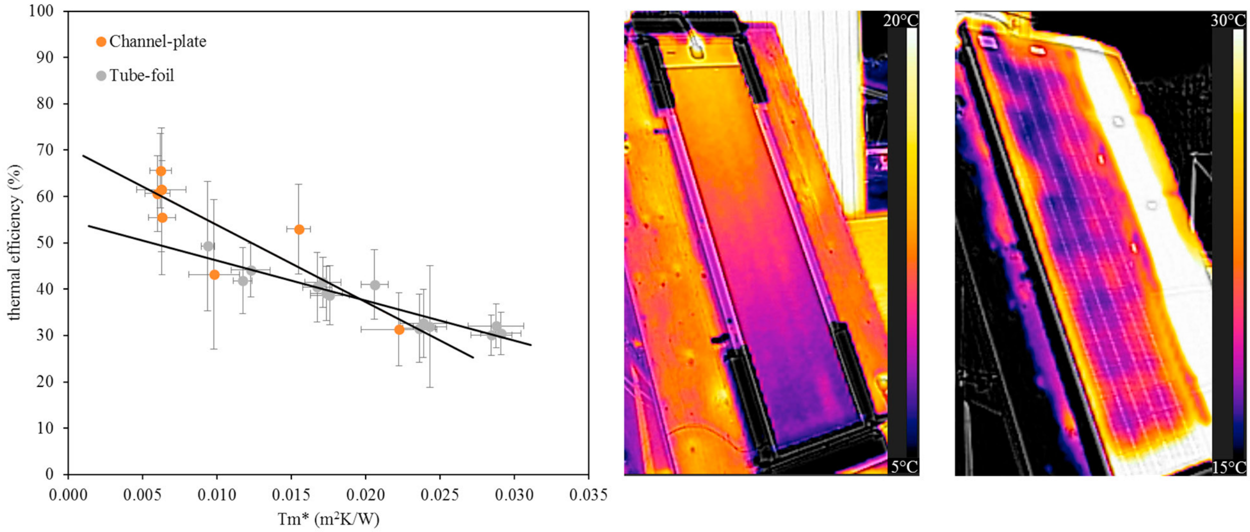

Fig. 3. Thermal efficiency as a function of reduced temperature and IR measured surface temperature distributions for channel-plate (left) and tube-foil (right) prototypes.

The channel-plate design turned out to be more sensitive to heat exchange with the ambience and more efficient close to ambient temperature conditions as compared to the tube-foil design. For the channel-plate design, the IR image shows steady increasing temperatures from the water inlet at the bottom to the water outlet at the top. In contrast, a patchy temperature distribution was observed in the tube-foil design, indicating that the contact between the solar cell and thermal collector was irregular. The surface waviness of the tube foil collector did not allow for a homogeneous contact with the flexible thin-film solar module.

3. Numerical analyses

To study the influence of collector design, materials and attachment of solar module to the thermal collector on collector performance computational fluid dynamics (CFD) simulations were performed using ANSYS Workbench 17.2 [10]. The relevant heat transfer mechanisms considered are conduction inside the solid domains, convection from the solid to the fluid domains (water and ambient air) as well as absorption, transmission and reflection of incoming solar radiation and outgoing thermally emitted radiation. The solar cell was modeled as a composite consisting of an absorbing CIGS layer, which is encapsulated with semitransparent ethylene vinyl acetate (EVA) films in between a semi-transparent front sheet and an opaque back sheet. The thermal collector was modelled as a solid-fluid composite with thermal insulation at the backside. EVA layers and the bond between the solar module and thermal collector were modeled by thermal contact resistances. Convective losses to the environment were modeled with an empirical correlation [11]. The required material properties i.e. thermal conductivity, density, specific heat capacity, kinematic viscosity, thermal diffusivity, extinction coefficient, refractive index and emissivity were taken from literature [11-14].

In the default configuration, irradiation of 800 W/m^2, wind speed of 2 m/s, water inlet temperature of 20°C and an ambient air temperature of 20°C are chosen. For the solar module front sheet and back sheet, 1mm Teflon and PET layers are assumed, respectively. For the EVA layers and bond between solar module and thermal collector, thermal impedances of 1.4E-3 m^{2}K/W and 2.1E-2 m^{2}K/W, respectively, were assumed. To account for the experimentally observed reduced adhesion quality when attaching a flexible solar module to a flexible thermal collector, an increased thermal impedance of 2.9E-2 m^{2}K/W was chosen for the tube-foil design. In open circuit mode and at zero reduced temperature, this resulted in thermal efficiencies of 73.1% and 61.5% for the channel-plate and tube-foil designs, respectively. These values are close to the experimentally observed values.

Several design variations and their impact on thermal performance at zero reduced temperature were studied (Fig. 4, left). Replacing the solar modules' 1mm Teflon front sheet with a 3 mm glass front sheet decreased thermal efficiencies by 3-4%. Glass has a smaller extinction coefficient but higher reflectivity than Teflon. In agreement with previous studies [15], Teflon outperforms glass because of the dominant reduction in reflection losses. However, glass is preferred from a building integration perspective: It is well-known in the built environment, durable and allows for superior architectural quality. When replacing the PET solar module back sheet with a 0.5mm aluminum sheet, a thermal efficiency increase of 5-6% was achieved. By using a material with higher thermal conductivity, the heat transfer between the solar cell absorber and thermal collector is improved. An even better improvement is achieved by minimizing the thermal resistance of the bond, e.g. assuming that the solar cells are directly laminated onto the thermal collector. A thermal efficiency increase in the range of 20-25% relative to the default configuration is expected. Finally, a design entirely based on plastic materials has been considered. As expected the lower thermal conductivity results in a decrease in efficiency. Interestingly, in the channel-plate design only a small decrease of < 2% is predicted. The direct contact of the water flow with the thermal collector surface reduces the impact of low thermal conductivity materials.

The bond between solar module and thermal collector turned out to be the most dominating influence on thermal performance at zero reduced temperature. Contact resistance is a function of several geometric, physical, and thermal parameters and challenging to properly characterize [16]. Therefore, a sensitivity analysis is presented in Fig. 4 (right) with the smallest and largest values representing the thermal impedances of an EVA layer without air inclusions and a 2mm air gap, respectively. An incomplete wetting of the contacting surfaces and entrapment of air can easily reduce the thermal efficiency by 10-20% as experimentally observed in the case of the channel-plate prototype versus tube-foil prototype.

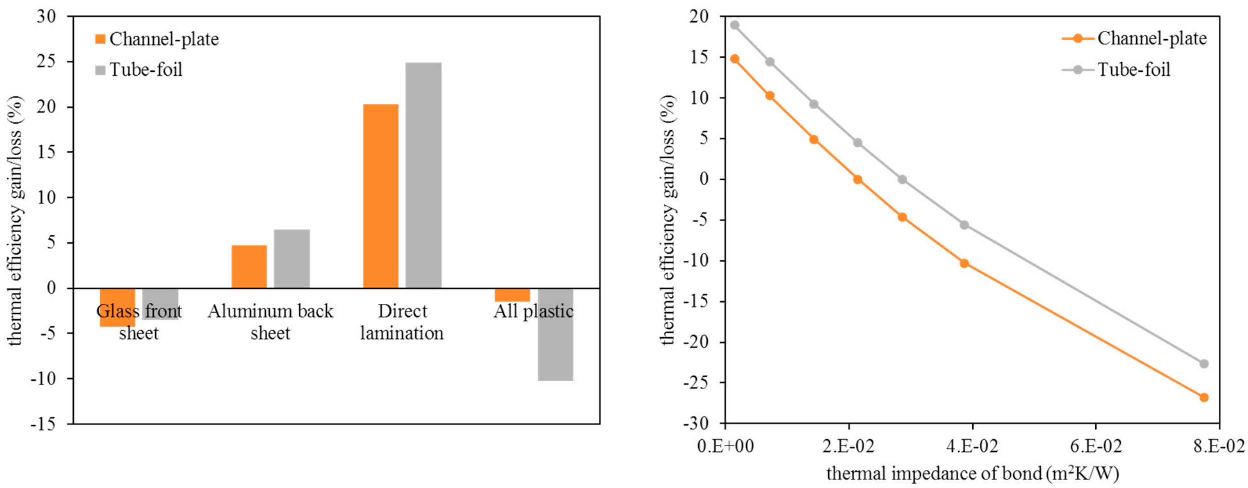

Fig. 4. Influence of design variations (left) and thermal impedance of bond between solar module and thermal collector (right) on thermal efficiency relative to the default configuration.

4. Discussion and conclusions

Unglazed PVT collector concepts to cover electricity and heat demands of LowEx Buildings have been experimentally and numerically evaluated. A promising solution was found in the direct lamination of CIGS cells onto a channel-plate thermal collector resulting in a super-light (<4kg/m^2) and ultra-thin (<4mm) PVT collector simplifying building integration. Besides the roof, installation on the building façade is possible which – in the mid latitudes of Europe – results in a more even energy production over the year and better match with the building's energy demand

[7]. In combination with a heat pump, the proposed collector design is well suited to cover electricity and heat demand of net-zero and plus-energy buildings.

The proposed channel-plate design allows the use of cheap plastic materials and results in small temperature gradients which further improves the solar cell electricity yield. The superior thermal contact is expected to yield electric and thermal efficiencies of up to 15% and 60%, respectively. The lightweight design reduces the amount of materials used and associated costs as well as environmental impacts. Special attention is needed in the design of the header tubes to obtain a sufficiently reliable construction with low-pressure loss and even flow distribution [17, 18]. Form and location of hydraulic as well as electric connections between the PVT collectors and building systems will be crucial for successful architectural integration and need further considerations. Last but not least, the impact of glassless collectors on durability and certification for building integration need to be evaluated.

The optimum collector operating conditions and interaction with the various building components such as heat pumps, TABS and geothermal boreholes are currently being studied by means of system analyses. It is expected that the associated reduced dependence on thermal storage will lead to an economic advantage. Further research is planned to investigate the efficacy of unglazed PVT collectors for night cooling and exploitation of the ambience as an anergy source. In general it is expected, that the targeted low operating temperatures help to reduce complexity and minimize challenges related to high stagnation temperatures.

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