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A PVT collector concept with variable film insulation and low-emissivity coating

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Abstract

Hybrid photovoltaic-thermal (PVT) collectors co-generate solar electricity and heat in a single component with an optimum utilization of space. Spectrally selective but transparent low-emissivity (low-e) coatings are a proven method to reduce thermal losses. However, overheating and stagnation are critical issues for these collectors due to material degradation, thermal stress, and low electrical efficiency.

This paper presents a PVT collector concept with variable film insulation as overheating protection. An inflatable glass-film cushion regulates thermal losses. Performance and stagnation tests were carried out with a prototype. During normal operation the collector achieves a high thermal efficiency. In periods of standstill, the deflated cushion has a high heat dissipation rate by deactivating the low-e coating. Stagnation temperatures are thus limited to 95 °C. To conclude, the PVT collector combines the advantages of glazed and unglazed PVT collectors which are a high thermal efficiency and low stagnation temperatures.

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Keywords: hybrid photovoltaic-thermal (PVT) collector; spectrally selective coating; switchable insulation; overheating protection; thermal management

1. Introduction

Hybrid photovoltaic/thermal (PVT) collectors convert solar energy into both electricity and heat in one component. Typical photovoltaic (PV) modules have an efficiency of 10 – 20 %. The major part of the solar spectrum remains

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unused and is transformed into heat. PVT collectors use the excess heat by coupling the solar cells thermally to a fluid. Thus, they have the potential to make optimum use of the solar resource with the maximum utilization of available space.
PVT collectors can be categorized according to their design (unglazed, glazed, and concentrating) [1]. Each design has its specific temperature levels and accordingly suitable applications. Unglazed PVT collectors are optimized towards electrical performance but deliver heat at low temperature levels. Glazed PVT collectors reach higher temperature levels because of reduced thermal losses due to a transparent cover. Low-emissivity (low-e) coatings are a proven measure to further decrease radiative losses. Analogous to spectrally selective solar thermal absorbers low-e coatings feature low emissivity in the infrared spectrum but a high transmittance in the solar spectrum. At Fraunhofer ISE, a novel low-e coating was developed which is specifically optimized for the application in PVT collectors. With this coating radiative losses are reduced by 80 %, so that a thermal efficiency similar to state-of-the-art solar thermal, flat plate collectors is achieved [2]. Hence, glazed PVT collectors with low-e coatings are a suitable technology for conventional solar thermal applications such as hot water preparation or space heating [3]. However, overheating is an issue exacerbated by low-e coatings. Stagnation temperatures can exceed 150 °C. Materials employed in PV modules, especially EVA, are not designed to withstand these temperatures. Moreover, high stagnations temperatures increase thermal stress and the occurrence of brittle cell connectors [4].
Fortuin [5] describes two approaches for high-temperature PVT collectors: temperature resistant materials [6] or overheating protection. A switchable insulation limits temperatures in both the collector and the hydraulic system by actively increasing heat losses. Additionally, the switchable insulation enables a flexible, more efficient operation. By adjusting instantaneous efficiencies the generation priority can be switched between electricity and heat-driven operation.
The collector concept presented in this paper uses a fluoropolymer film to achieve a variable insulation. Fluoropolymer films such as ETFE, FEP, or PTFE are used in architectural façade applications, in solar thermal collectors as convection barrier, and in greenhouses. Different inflatable glass-film-combinations for flexible greenhouse systems were investigated in [7]. A variable film insulation for solar thermal collectors is used as overheating protection in [8] and to achieve variable heat dissipation rates by adjusting convective losses in [9]. In the presented PVT collector concept the film is sealed hermetically at the edges to the low-e glass. A small air pressure stabilizes the cushion and ensures low thermal losses. Deflating the cushion increases heat losses and thus reduces collector temperatures during stagnation.

2. Collector concept and construction

The basis for the collector concept forms a flat plate, glazed, liquid-type PVT collector design. A fluoropolymer film replaces the external glass cover as used in conventional flat plate collectors. Inflating and deflating the glass-film cushion regulates the heat losses and enables an effective switchable insulation (Fig. 1). The requirements for the collector are a high efficiency during operation combined with low stagnation temperatures comparable to unglazed PVT collectors to avoid damage and increase electrical efficiency. The overheating protection needs to be fail-safe ensuring that even during power outages and failure of the hydraulic system critical temperatures are avoided.
For this purpose, we characterized films of different materials and thicknesses. The radiative heat losses in the

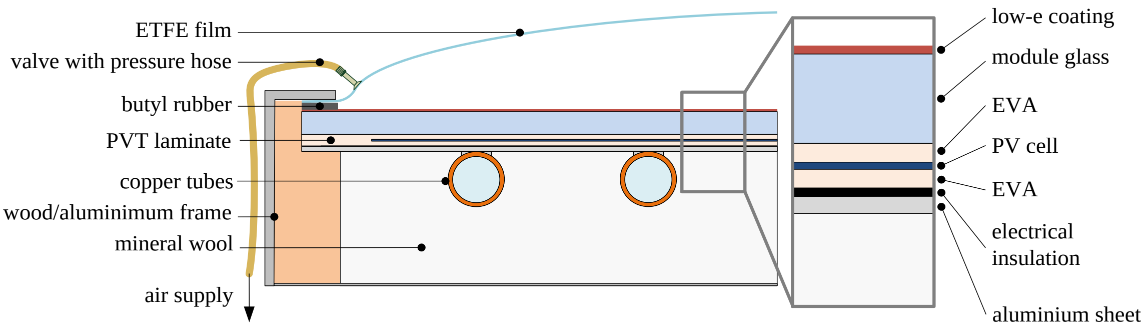

Fig.1. Schematic drawing of the collector concept with inflated ETFE cushion.

inflated and deflated mode were studied by means of infrared thermography in conjunction with hot plate measurements. The radiative characteristics of ETFE, FEP, and PFA differ only slightly. Thicker films are advantageous regarding mechanical stability and a low transmittance for infrared radiance. Thinner films are more suitable for the deflated mode, where the film's elasticity achieves a smooth contact between film and glass. Thermal losses in the inflated and deflated cushion were studied with a calibrated thermal collector model. Based on this model an ETFE film with a thickness of 100 μm was selected, owing to its good balance between the mentioned requirements.

The PVT laminate consists of PV cells embedded between a low-e coated module glass and a sheet-and-tube absorber. For a good thermal contact the PV cells were directly laminated on the aluminium sheet [10]. 32 monocrystalline silicon solar cells are connected in series. They feature a rated electrical efficiency of $\eta_{el,STC}$ = 18.2 % and a power temperature coefficient of β = 0.43 %/K. A thin electrically insulating layer was spray-coated on the aluminium sheet of 0.92 m² before lamination. Two layers of EVA encapsulate the PV cells. Copper tubes forming a meander were laser-welded to the aluminium sheet with a tube spacing of 77 mm.

The silver-based low-e coating was developed specifically for the application in PVT collectors with an optimized balance between emissivity and transmittance. A 4 mm thick low-iron soda lime glass is used as glass substrate. The low-e coating was sputter-deposited on the PVT module glass on a horizontal sputtering system at Fraunhofer ISE. A low emittance of ε_{373K} = 0.12 and a high transmittance in the solar spectrum of $\tau_{AM1.5}$ = 0.78 are achieved. In the responsive spectrum of silicon solar cells a high transmittance of even $\tau_{c\text{-}Si}$ = 0.87 is reached.

Butyl rubber seals the glass-film cushion at its edge compound. A conventional Schrader valve is inserted and also sealed with butyl rubber. During normal operation a low air pressure of 20 mbar stabilizes the cushion and the air layer leads to a good thermal insulation. The film takes the form of a curved cushion with the distance between film and glass varying between 3 mm and 35 mm. On average, the distance amounts to 26 mm. During stagnation the cushion is deflated which increases convective and radiative heat losses. An alternative construction without external air supply can be achieved by mounting the film on a frame whose distance to the module glass can be varied, for example with thermal actuators.

The PVT laminate is mounted in a wooden frame enforced by an aluminium L-profile. 80 mm thick mineral wool is used as rear insulation. The PVT laminate is pressed against the aluminium profile to ensure air tightness of the ETFE-glass-cushion over longer periods of time. Fig. 2 shows the assembled PVT collector prototype in both inflated and deflated modes.

(a) inflated, front view (b) inflated, lateral view (c) deflated, top view

Fig. 2. PVT prototype in the solar irradiance simulator.

3. Performance tests of the PVT prototype

The performance of the PVT collector with variable film insulation was tested in the solar irradiance simulator of the accredited test facilities of Fraunhofer ISE. Thermal performance measurements of the collector in inflated and deflated mode were conducted according to ISO 9806 [11]. The PVT collector was operated in hybrid mode with an attached electronic load in the form of a Maximum Power Point (MPP) tracker.
Fig. 3 shows the resulting thermal and electrical efficiency curve in both collector modes. Table 1 summarizes the corresponding performance parameters.

3.1. Thermal efficiency

The thermal efficiency $\eta_{thermal}$ in the inflated operating mode achieves a good performance. The ETFE cover reduces convective losses substantially compared to unglazed PVT collectors. Thus, the wind dependency of thermal efficiency is minimized and high fluid temperatures are reached even during windy conditions. Additionally, the spectrally selective low-e coating minimizes radiative losses. With the good thermal insulation the collector is able to deliver significant thermal yields even during the transitional period and winter.
At the same time the collector is protected against high temperatures by the switchable insulation. With the deflated cushion the PVT collector has the same characteristics as unglazed PVT collectors with high heat losses and low stagnation temperatures. This indicates that the film in contact with the glass deactivates the low-e coating achieving high radiative heat losses. Additionally, high convective heat losses occur owing to the absence of an insulating air layer and the direct exposure to wind. Thus, the variable insulation covers a wide switching range from U_{Loss} = 5 W/m²K to U_{Loss} = 18 W/m²K.
Measurements of the stagnation temperature were conducted in worst-case scenario, which are no wind conditions and open circuit mode without electrical load. The absorber temperature did not exceed 94.5 °C at two thirds of the collector height. The overheating protection consequently allows the usage of cost-effective materials in both the collector and the solar thermal system. Thus, costs can be reduced significantly, for example by a wide usage of polymer materials in the collector, piping, and system.
A test sequence was run to analyse the dynamic behaviour of the variable film insulation. Within 8 minutes, the collector is able to switch from the fully inflated to the deflated mode. The original state with inflated cushion was re-established within another 8 minutes using a low-cost blower with a nominal power of 19 W.

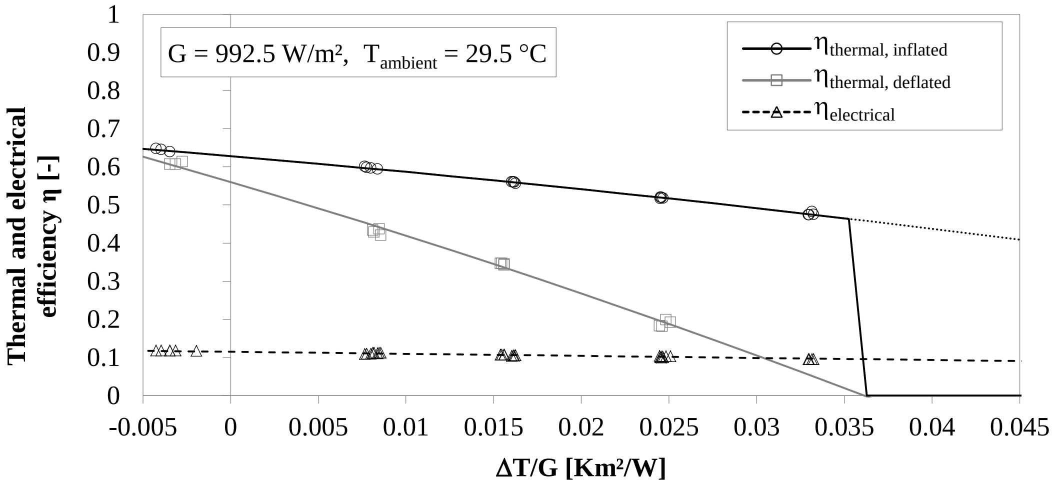

Fig. 3. Thermal and electrical efficiency of the PVT collector in inflated and deflated mode under hybrid MPP conditions.

Table 1. Performance test results for the inflated and deflated collector, measured in hybrid MPP mode.

Parameter	Symbol	inflated mode	deflated mode
thermal conversion factor [-]	$\eta_{th,0}$	0.63	0.56
linear heat loss coefficient [W/(m²K)]	a_1	3.92	13.5
temperature dependence of heat loss coefficient [W/(m²K²)]	a_2	0.021	0.056
photovoltaic efficiency at ΔT = 0 K	$\eta_{el,0}$	0.115	0.115
standard stagnation temperature in OC mode	T_{stag}	154 °C	94.5 °C

However, the performance of the PVT collector still has potential for optimization as simulation results show. The conversion factor can be increased to $\eta_{th,0}$ = 0.68 by using FEP instead of ETFE and by an improved low-e coating with less reflection losses. The solar transmittance of FEP films is 2 % higher than the transmittance of ETFE films. Compared to a reference coating 3 % higher reflection losses are observed. A PVT collector of larger dimensions offers lower heat losses, especially at the edges. Inflating the hermetic cushion with noble gases instead of air reduces convective heat losses further.

3.2. Electrical efficiency

The good thermal performance comes at the expense of a slightly lower electrical performance compared to unglazed PVT collectors. At ΔT = 0 K, which corresponds to mean cell temperatures of 36 °C, the electrical efficiency amounts to $\eta_{el,0}$ = 11.5 %. No difference in electrical efficiency is observed between the inflated and deflated mode. However, the lower stagnation temperatures in the deflated PVT collector lead to a boost of electrical efficiency. During stagnation the electrical efficiency amounts to $\eta_{electrical}$ = 9.6 % of the deflated collector compared to 5.9 % of the inflated collector. Hence, the switchable insulation can be used to optimize the electrical yield during periods of standstill and low thermal demand by an intelligent thermal management. TRNSYS simulations indicate that the annual electrical yield in a combi system can be increased by 10 % without affecting the thermal yield [12].
The electrical efficiency can also be further optimized. Optical measures to increase transmittance of film and coating result in a higher photon density and consequently a higher electrical efficiency. In contrast to conventional glazed PVT collectors, partial shading of the PV cells at the module edges is no issue. Therefore, more aperture area can be occupied by active PV cells increasing the packing factor and thus electrical efficiency further.

4. Summary and Outlook

With spectrally selective and transparent low-e coatings high efficiency PVT collectors with low thermal losses can be built. However, temperatures exceed 150 °C during stagnation owing to the good thermal insulation. PVT collectors can be protected against overheating by a switchable insulation. In this paper a promising collector concept was presented, in which an inflatable ETFE-glass-cushion forms a switchable insulation. During normal operation, the ETFE-glass-cushion is inflated and low thermal losses occur. During periods of low thermal loads the ETFE-glass-cushion is deflated, so that the low-e coating is in principle deactivated and high convective and radiative losses occur.
A PVT collector prototype with variable film insulation was built and the performance and stagnation temperatures were measured. During normal operation, a high thermal efficiency was reached. With the film smoothly attached to the glass low stagnation temperatures comparable to unglazed PVT collectors are reached. Thus, the switchable insulation can be used to limit collector and system temperatures. At the same time, it can be used to respond to current thermal and electrical demand and realize a flexible, demand-oriented operation, increasing the overall energy yield.
After the first successful demonstration of the practical viability of the collector concept there is still significant research required. The long-term durability of the film at elevated temperatures, UV radiation, and hailstorms needs to be studied. The overheating protection needs to be designed in a passive, fail-safe way, which deflates the collector passively during all sorts of system failures. The parasitic energy consumption of the ventilator needs to be

evaluated and weighed against the gain of electrical yield or other possible benefits such as night cooling. Finally, the overheating protection can also be applied to polymer collectors, where a big potential for cost reduction is seen.

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