Experimental Investigations on Photovoltaic-Thermal Arrays Designed for the Use as Heat Pump Source

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Abstract

Uncovered, liquid-based photovoltaic-thermal (PV-T) collectors can be combined with ground-coupled heat pump systems for different purposes: to increase the evaporator temperature, to regenerate geothermal resources or for pre-heating domestic hot water. This paper experimentally investigates the behavior of a novel PV-T panel with enhanced ambient heat transfer properties and primarily conceived for the operation as the sole heat source for brine-to-water compression heat pumps. After presenting the results of the thermal efficiency measurement of the panel, which attest its unusual parameters (c_1= 23 W/m²K, c_3 = 7.6 J/m³K, c_6 = 0.1 s/m), we report on the long-term performance tests carried out on large roof-mounted PV-T fields at two different locations in Germany. The investigation focuses on the impact of real environmental and installation conditions on the performance of the field as ambient heat exchanger, operating at fluid temperatures below ambient air temperature. The results confirm the high overall heat transfer coefficient U of the field, up to 40 W/m²K, which is reduced by about 20% in comparison to the U-value determined for the single panel, however. The reduction can be attributed to a large extent to the high sensitivity of the collector design to convective heat transfer mechanisms and to the different wind exposure during the tests. For the same reasons we report a 30% decrease in the U-value compared to the basic configuration by using joint plates to cover the gaps of the field with the aim of improving the reliability and aesthetics of the installation.

Keywords: photovoltaic-thermal collector, heat pump, heat exchanger, heat transfer coefficient, field test

1. Introduction

Uncovered, liquid-based photovoltaic-thermal (PV-T) collectors can be combined with brine-to-water heat pumps as additional heat source to increase the temperature of the heat pump evaporator, to regenerate the ground as well as to directly pre-heat domestic hot water or assist low-temperature heat distribution systems (Kern et al., 1978; Zondag, 2008; Bertram et al., 2012; Hadorn, 2015). In recent years, a novel PV-T concept has been developed and implemented by the German company Consolar Solare Energiesysteme GmbH. This device is able to serve as the sole heat source for the connected heat pump, and to provide for high system efficiencies (Leibfried, 2018; Consolar, 2018). This integration route has been intensively investigated in previous works (i.e. O'Dell et al., 1984; Ito et al., 1999; Bridgeman and Harrison, 2008), but in most cases the optimization of the collector design hasn't been addressed.

The novel PV-T concept offers a promising alternative to conventional HP sources, like geothermal heat and ambient air. Thanks to a specifically shaped heat exchanger, which is mounted on the rear side of the PV module, the heat production from both the sun and the ambient air is optimized. The suitability and the potential of such collector design in heat pump systems have been previously indicated by means of experimental tests on constructively comparable PV-T prototypes and simulation studies (Helbig et al., 2018).

Related heat supply concepts are currently under investigation in two R&D projects carried out at the Institute for Building Energetics, Thermotechnology and Energy Storage (IGTE) as well as the Institute for Solar Energy Research Hamelin (ISFH) in Germany using large-format test fields. These projects are aiming at a detailed

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analysis of the collector behavior on system level, under controlled and representative operating conditions. The present paper reports and discusses first results, focusing on the heat transfer coefficient of the PV-T field.

2. Preliminary tests of PV-T modules

The investigated PV-T collector is provided with a new heat exchanger featuring additional metal fins soldered to the meander pipe in order to increase the heat transfer surface, which then results 10 times larger than that of the PV module. The special geometry enhances the heat transfer from the ambience and significantly improves the heat production at low irradiation. This property makes the new device particularly suitable for the use as heat source in heat pump systems. The heat exchanger is attached to the rear side of the PV module through an adhesive layer ensuring an effective transfer of the absorbed solar energy into the fluid.

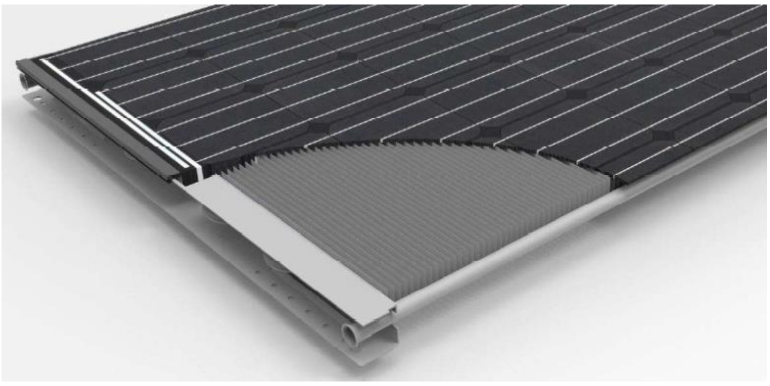


Figure 1: Sectional view of the investigated PV-T collector: the finned heat exchanger below the PV module exhibits a surface ten times larger than the module surface (Consolar, 2018)

The thermal efficiency of the collector was determined by means of outdoor measurements at IGTE according to the Standard ISO 9806 (2017) as part of a Solar Keymark certification, using the quasi-dynamic test method. The correspondent parameters in MPP operation mode (Maximum Power Point) are given in Table 1 (Solar Keymark, 2019). Therein, $\eta_{0,b}$ represents the zero-loss efficiency for beam radiation, c_1 the heat loss coefficient at $T_{f,m}$ - T_a = 0 (with $T_{f,m}$ = mean fluid temperature and T_a = ambient air temperature), c_3 the wind dependence of the heat loss coefficient, c_4 the sky temperature dependence of the heat loss coefficient, c_5 the effective thermal capacity and c_6 the wind dependence of the zero-loss efficiency. The collector exhibits a monocrystalline 72-cell PV module with a nominal power P_{MPP} = 340 W, an electrical efficiency η_{el} = 17.5% at Standard Test Conditions (STC) and a power temperature coefficient γ = - 0.39%/K.

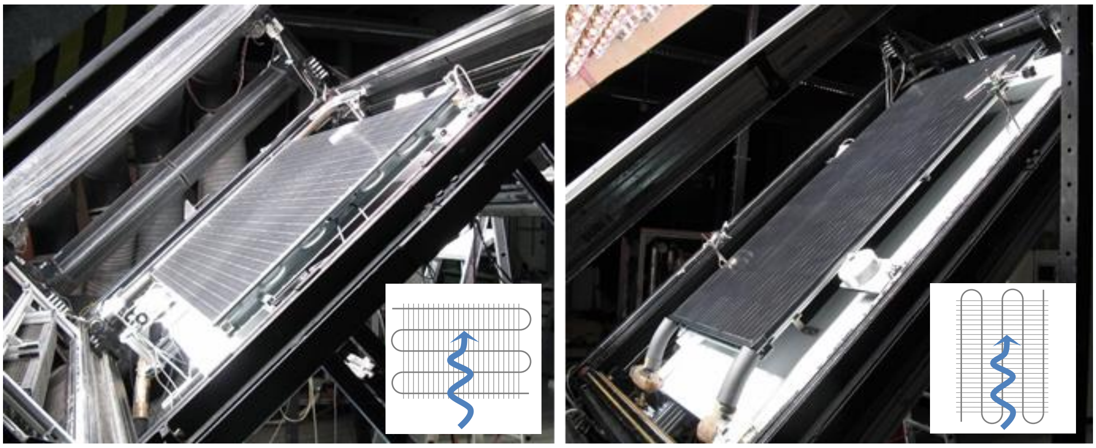
Table 1: Efficiency parameters of the PV-T panel referred to MPP operation mode and gross area (1.98 m²) according to Solar Keymark (2019)

Parameter	Value
$\eta_{0,b}$ [-]	0.468
c_1 [W/(m²·K)]	22.99
c_3 [J/(m³·K)]	7.57
c_4 [-]	0.434
c_5 [kJ/m²K)]	26.05
c_6 [s/m]	0.067

The results attest the high heat loss coefficients of the collector compared to uncovered PV-T on the market (cf. Broetje et al., 2018), where c_1 usually ranges from 6 to 13 W/m²K and c_3 from 1 to 2 J/m³K.

Due to the parallel-plate arrangement of the heat exchanger fins placed on the rear side of the module (cf. Figure 1) a strong directional dependence of the convective heat transfer must be expected, which however cannot be assessed by the standard efficiency measurements for solar thermal collectors.

To investigate this effect, the PV-T collector was tested at the ISFH in two different mounting configurations: (a) with horizontally oriented meander tubes and upward-directed fin channels (as specified by the manufacturer) as well as (b) with vertically oriented meander tubes and horizontally oriented fin channels. The thermal performance was determined by means of indoor measurements with a solar simulator according to the steady-state test method. The airflow produced by the wind generator streams the module parallelly or perpendicularly to the fin alignment, as schematically illustrated in Figure 2.



(a) (b)

Figure 2: View of the PV-T collector during efficiency measurements in the solar simulator of ISFH with horizontally (a) and vertically (b) oriented meander pipes. Blue arrows indicate the direction of air flow by the wind generator.

The heat loss coefficients determined in these measurements are given in Table 2. The results confirm that the wind-dependent parameters c_3 and c_6 in the horizontal configuration (a) are considerably higher than those in the vertical one (b) due to different airflow conditions. The results of the standard test at IGTE (cf. Table 1), which was performed outdoors under natural meteorological conditions and thus variable wind direction, fall within the range of the figures measured indoors.

As the characteristics of the artificial wind in the solar simulator are not fully comparable to those of natural wind, the indoor measurements have to be validated by outdoor tests. These first results already give an idea of the unusual behavior of the collector and its strong sensitivity to the wind direction.

Table 2: Heat loss coefficients from the indoor measurements at ISFH with horizontal and vertical installation of the PV-T panel[1], referred to MPP operation and gross area

Parameter	Horizontal	Vertical
c_1 [W/(m²·K)]	21.51	19.21
c_3 [J/(m³·K)]	14.21	5.58
c_6 [s/m]	0.10	0.05
$U = c_1 + c_3 \cdot u$, for u = 1.3 m/s [W/m²K]	39.97	26.46

3. Field test facilities and procedure

Due to the special design of the PV-T collector, which enhances the ambient heat transfer, a strong dependence on the specific installation conditions must be expected. To analyze and evaluate the performance in real operation, large collector arrays have been installed on test roofs and investigated at ISFH and IGTE. Each array consists of nine PV-T modules (3 x 3 arrangement, total gross area 17.8 m²) featuring the same design and the

[1] The heat loss coefficients have been calculated from the results of the steady-state measurements according to the following conversion formula: $c_1 = b_1$, $c_3 = b_2$ and $c_6 = b_u \cdot \eta_{0,hem}$

same PV-panels of the single modules described in Section 2. The specific goals, measurement procedure and equipment of the tests are presented in the following.

3.1 Test field at IGTE

The IGTE is located on the premises of the University of Stuttgart (latitude: 48.75°N; altitude: 473 m s. l.) in the south-German uplands of the state Baden-Württemberg. The PV-T field is installed on a south-facing test roof with a slope of 47° and is operated with a cooling thermostat at a fixed predefined collector inlet temperature as shown in Figure 3 (b). In comparison to a real solar assisted heat pump system, the collector can be operated in a wider thermal output range, depending on the occurring weather conditions (in particular the ambient temperature). This enables the acquisition of more general information over the measurement period about the behavior of heat pump systems with very different dimensioning. The collector test field was initially set up in the basic configuration in accordance with the manufacturer's specifications at a distance of approximately 12 cm from the roof (cf. Figure 3a).

(a) (b)

Figure 3: Basic configuration of the PV-T field investigated at IGTE (a) and schematic representation of the operation mode (b).

In a second step additional metal plates have been installed between adjacent modules as well as between the PV-T field and the roof, in order to ease the removal of snow or foliage, to prevent animal nest-building and for aesthetical reasons (cf. Figure 4). For the evaluation, wind speed, ambient air temperature and hemispherical solar radiation at collector level, fluid temperatures at the field inlet and at the collector outlet for each collector row, as well as mass flow of the collector fluid are recorded.

(a) (b)

Figure 4: Perforated plates used to cover the gap between the single collectors of the PV-T field (a) and overall view of the PV-T field configuration with perforated and side plates (b)

During the project the investigations at IGTE focus on the impact of the following aspects on the performance of the PV-T field:

- Wind velocity
- Dimensioning ratio heat pump / collector area
- Free-standing collector mounting versus roof mounting
- Mounting distance to the roof cladding (with parallel roof mounting) and collector slope
- Use of metal plates to cover the gaps between the single PV-T modules
- Condensation, icing and snow cover

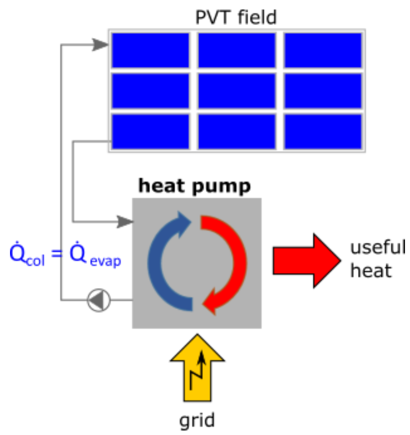
The paper documents the first results of the tests and compares them to the measurements of the single modules. It specifically addresses the influence of the metal plates on the thermal performance of the field and analyses the different behavior of the single collector rows.

3.2 Test field at ISFH

The ISFH is located in the community of Emmerthal in the German state Lower Saxony (latitude: 52.07°N; altitude: 89 m s. l.), at the fringe of the north-German lowlands. The PV-T field is installed on a south-facing test roof at a slope of 38°, next to an identical field consisting of only PV modules (cf. Figure 5a). This arrangement ensures a direct comparison between the electrical performance of the thermally activated (PV-T) and non-activated (PV-only) panels.

The PV-T field is hydraulically connected to a fluid circuit provided with a heat pump as shown in Figure 5 (b). The system is integrated into a hardware-in-the-loop test environment, which can reproduce the energy demand scenario of a single family house during the course of a year according to the reference building SFH 45 defined by the IEA Task 44. This enables dynamical testing of the PV-T field under realistic operating conditions. The heat and domestic hot water demands are modelled with the software TRNSYS and the related energy fluxes are emulated by using loop-controlled thermostat units and a tap cascade. The hydraulic design of the test facility also allows the operation at constant inlet temperature and constant mass flow, so that the PV-T field can be evaluated on the basis of the Standard ISO 9806 according to both steady-state and quasi-dynamic methods, which ensures the comparability with the test results at IGTE.

(a)



(b)

Figure 5: PV-T field (right-hand side) and PV field (left-hand side) installed on the ISFH test roof (a) and scheme of the thermal operation of the PV-T field (b).

In addition to the measurement equipment implemented at IGTE, the ISFH test setup also records wind direction, relative ambient air humidity, diffuse radiation and long-wave irradiation at collector level, as well as module and air temperatures, relative humidity and flow velocity at different positions in the air gap between the PV-T field and the roof. The sensors arrangement of the ISFH test facility is shown schematically in Figure 6.

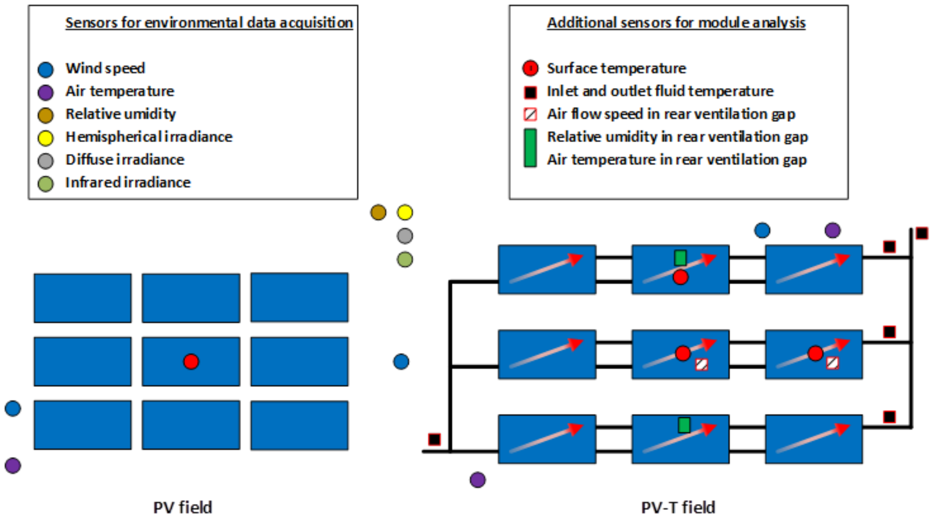


Figure 6: Schematic representation of the sensors used for data acquisition at ISFH (left: PV-field; right: PV-T field)

The investigations at ISFH during the project focus on the following research topics:

- Comparison of the electrical efficiency of PV and PV-T field in different operating modes
- Impact of condensation and icing on performance and reliability
- Impact of wind direction on performance
- Impact of air velocity in the gap between collectors and roof on performance

The paper documents the first test results and compares the performance of PV-T field and single PV-T panel, specifically addressing the influence of the wind exposure.

4. Field test results

The measurements were carried out in the winter season 2018 - 2019 to analyze the performance of the PV-T fields as ambient heat exchangers in dark operation, i.e. during periods without solar irradiation.

We use the overall heat transfer coefficient U between the PV-T field and the outdoor environment as assessment criterion, which is calculated by

$$U = \dot{q} \, / \, (T_a - T_{field,m}) \qquad \text{(eq. 1)}$$

T_a represents the ambient temperature and $T_{field,m}$ the average fluid temperature of the PV-T field (mean value of inlet and outlet fluid temperature $T_{field,in}$ and $T_{field,out}$). $\dot{q}$ denotes the heat flow from the outdoor environment to the PV-T field. The radiative heat exchange between PV-T and cold sky, which can significantly contribute to the heat flow, hasn't been considered separately. Under steady-state conditions, the heat flow $\dot{q}$ corresponds to the thermal output of the PV-T field $\dot{q}_{field}$ according to:

$$\dot{q} \approx \dot{q}_{field} = \dot{m} \, c_p \, (T_{field,out} - T_{field,in}) \, / \, A_{field} \qquad \text{(eq. 2)}$$

with $\dot{m}$, c_p and A_{field} representing the specific mass flow of the PV-T field, the specific heat capacity of the fluid and the PV-T field area, respectively. All measurements of the PV-T field addressed in this paper were carried out in open circuit (OC) mode, as the electrical performance of the PV needs not to be taken into account during the night-time tests.

4.1 Test results at IGTE

The presented results originate from nightly measurements carried out at IGTE from December 2018 to March 2019. Figure 7 and Figure 8 show the heat transfer coefficient U characterizing the heat flow from the outdoor environment to the PV-T field as calculated from Equations 1 and 2. Figure 7 documents the results for the basic field configuration, which exhibits gaps between the PV-T modules and also between the field and the roof. Figure 8 documents the results for the modified field configuration, which features perforated metal plates to cover the gaps between the modules and joint plates placed along the perimeter of PV-T field. Both figures also include an interpretation of the measured data in terms of a linear model which describes the heat transfer coefficient as a function of the specific heat flow $\dot{q}$ and the wind velocity u (measured at collector level).

The data analysis clearly attests the strong influence of these two parameters on the results. As the heat flow increases, higher temperature differences between the collector and its surroundings can be expected, which may induce free convection in the gravity field and enhance the overall heat transfer coefficient of the device; when this effect gets super-imposed by higher wind speeds, the influence of the heat flow on the heat transfer coefficient decreases accordingly. The relevance of free (temperature-driven) and forced (wind) convection is also confirmed by comparing the measurements with and without gap covers (cf. Figure 7 and Figure 8). The metal plates represent an additional flow resistance, which significantly reduces the heat transfer coefficient and also affects its dependence on wind velocity.

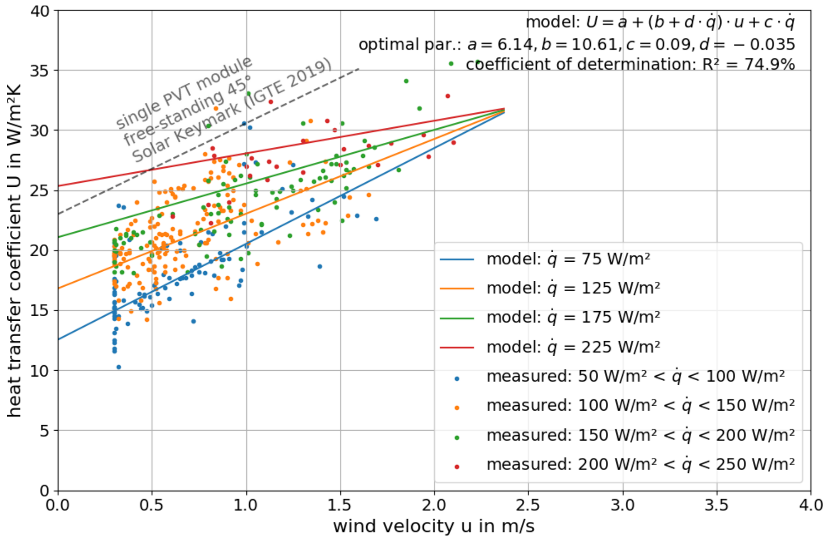


Figure 7: PV-T collector field without gap covering plates - Heat transfer coefficient *U* as a function of wind velocity *u* and transferred heat flow $\dot{q}$ (hourly mean *U*-values in times without irradiation and at stationary collector temperatures)

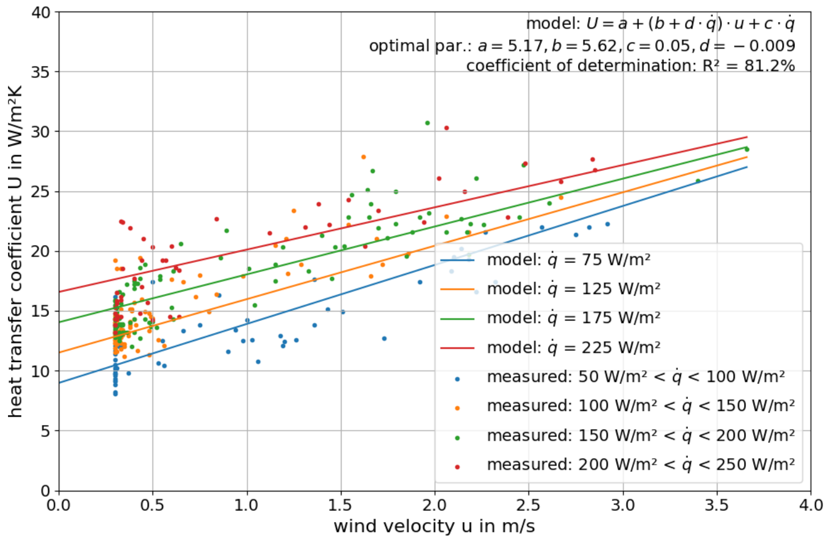


Figure 8: PV-T collector field with gap covering plates - Heat transfer coefficient *U* as a function of wind velocity *u* and transferred heat flow $\dot{q}$ (hourly mean *U*-values in times without irradiation and at stationary collector temperatures)

Generally, the IGTE data exhibit pronounced scattering of the heat transfer coefficient even if the evaluation is based on hourly mean values. We assume that the main reason for this is the missing information about the wind direction variability, which is not resolved at this location, but can strongly affect the results, as discussed in the following section (cf. Figure 11)[2].

Figure 7 also includes the linear correlation of the heat transfer coefficient for the PV-T collector in free-standing installation according to the parameters reported in Table 1 (grey dashed line). As expected, the heat transfer coefficient and the wind dependence for the single collector are higher than those for the roof-mounted field (for a standard field design, the area-specific heat flow amounts to about 200 W/m²). However, the quasi-dynamic test method does not take heat flow dependence into account, which makes a direct comparison of the results difficult.

Figure 9 analyses the uniformity of the heat transfer within the field for both configurations with and without cover plates. It shows that the ratio between the transferred heat flow in the upper and lower collector rows is greater than one for the majority of the recorded data. This means that the upper row of the field usually contributes more to the heat transfer. The non-uniformity of the flow distribution decreases with increasing wind velocity and heat flow. The use of additional cover plates on the other hand enhances the airflow resistance between modules and roof, and thus the non-uniform vertical distribution, as confirmed by the comparison of the upper and lower graphs of Figure 9. These results can be explained by the convective processes prevailing in the collector field: the air increasingly cooling down from the top to the bottom of the collector falls downwards; these cooling airflows result in a decreasing driving temperature difference between the collector surface and the adjacent air layers, which explains the lower heat flows determined for the bottom collector row (heat flow ratio > 1 in Figure 9). Wind, on the other hand, increases the air exchange and thus leads to a homogenization of the adjacent air layer temperatures.

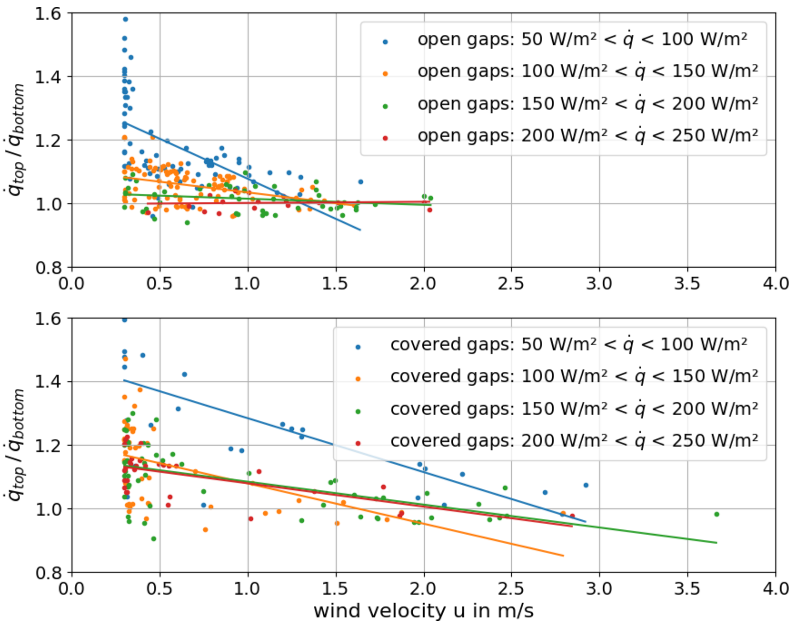


Figure 9: Vertical distribution of heat flow in the field, without (upper graph) or with (lower graph) metal plates. The heat flow ratio between the upper and lower collector rows is plotted as a function of the wind speed *u* and the total heat flow transmitted $\dot{q}$ (2-hour mean value in times without irradiation and at stationary collector temperatures)

Table 3 provides the numerical figures for coefficients c_1 and c_3 of the linear approximate equation as determined from the measurements for different heat flows as well as for the overall heat transfer coefficient *U* at a reference wind velocity u = 1.3 m/s. For comparison the coefficients of the single PV-T collector measurement according to Solar Keymark at IGTE are included. The results show that the *U*-value of the PV-T field in the basic configuration with open gaps is 20% to 30% lower than the *U*-value of the single collector. The reduction increases with decreasing specific heat flow. The use of cover plates additionally reduces the *U*-value by about 30%.

[2] The strong scattering of the results at wind velocities next to 0.3 m/s doesn't depend on the environmental conditions or the collector characteristics, but on the measuring range of the wind sensor used for the tests.

Table 3: Overview of the coefficients c_1 and c_3 of the linear approximate equation determined for different heat flows and of the resulting overall heat transfer coefficient U for PV-T field and PV-T collector measurements

Test configuration	Specific heat flow $\dot{q}$ [W/m²]	Heat loss / transfer coefficients c_1 [W/(m²K)]	c_3 [J/(m³K)]	$U = c_1 + c_3 u$ for u = 1.3 m/s [W/m²K]
Roof mounted field (Slope 47°) Outdoor test at IGTE without metal plates	75	12.5	8.0	22.9
	125	16.8	6.2	24.9
	175	21.1	4.5	27.0
Roof mounted field (Slope 47°) Outdoor test at IGTE with metal plates	75	9.0	4.9	15.4
	125	11.5	4.5	17.4
	175	14.0	4.0	19.2
Free-standing collector (Slope 45°) Outdoor test at IGTE (Solar Keymark, 2019)	-	23.0	7.6	32.9

4.2 Test results at ISFH

The ISFH data were recorded during 17 winter nights in December 2018 and January 2019. To analyze the heat transfer from the environment, the PV-T field was operated at a constant inlet temperature of -10 °C and at a constant mass flow of 900 kg/h (50 kg/m²h). Under the prevailing ambient conditions, the heat exchanger was most of the time at temperatures below 0 °C so that the PV-T modules exhibited surface icing. The recorded heat flow at a defined inlet temperature thus results not only from the ambient temperature, the sky temperature and the wind velocity, but also from the influence of condensation and icing. The ice formation mainly affects the upper surface of the PV-modules and the collector manifold. The fins of the heat exchanger exhibit a thin ice layer, but during the tests the fin interspaces do not freeze up entirely, not even after prolonged exposition to extreme temperatures. On the basis of these observations we expect the ice layer to have a stronger impact on conductive rather than on convective heat transfer mechanisms. It should be noticed, that the manufacturer has implemented a de-icing function in the system, which can be automatically or manually activated to deice the modules or to remove snow from the field. This function was not in use during the measurements, however. Deicing strategies and their impact on the system performance are subject of our ongoing investigations.

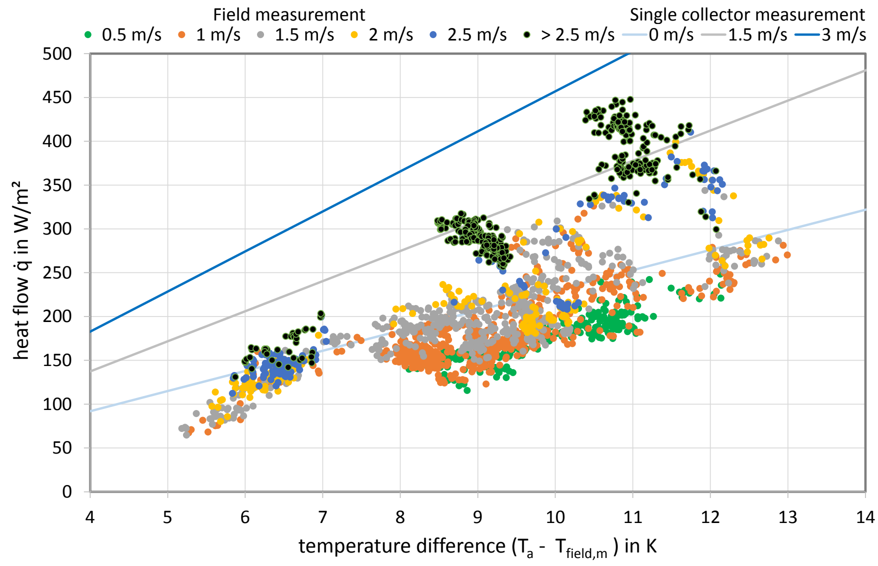


Figure 10: Specific heat flow as a function of the temperature difference between ambient air and collector fluid temperature as well as of the wind velocity (5-minute mean values)

The results of the measurements are provided in Figure 10. The data are presented in terms of the derived heat flow (5-minute mean values) as a function of the difference between ambient temperature T_a and mean fluid temperature of the PV-T field $T_{field,m}$, color-coded by the wind velocity u. For comparison the characteristic lines resulting from the heat loss coefficients c_1 and c_3 of the Solar Keymark test performed at IGTE on the single module reported in Table 1 are included in the graph.

The data analysis shows that for a given wind velocity, the heat production of the PV-T field is significantly lower than the one of the single PV-T modules. The difference depends on both environmental conditions and type of installation. On the one hand, wind speed has a stronger influence on the heat transfer of single modules than of larger collector arrays due to self-shielding effects. On the other hand, the ice layer represents for the field an additional thermal resistance between the environment and the fluid ($\lambda_{ice,\ 273K}$ = 2.2 W/mK).

Figure 11 shows the relation between the heat transfer coefficient U and the wind direction, which is resolved by the color code. The west direction is predominant, particularly at higher wind velocities (> 1.5 m/s). A more detailed analysis shows that for only 13% of the recorded data the wind comes from directions between SSE and SSW. This means that the collector field is most of the time streamed sideward, i.e. transversely to the alignment of the heat exchanger fins. On the basis of the indoor measurement results reported with single modules discussed in Section 3, the heat loss / transfer coefficients are expected to be significantly lower under these flow conditions than for other wind directions.

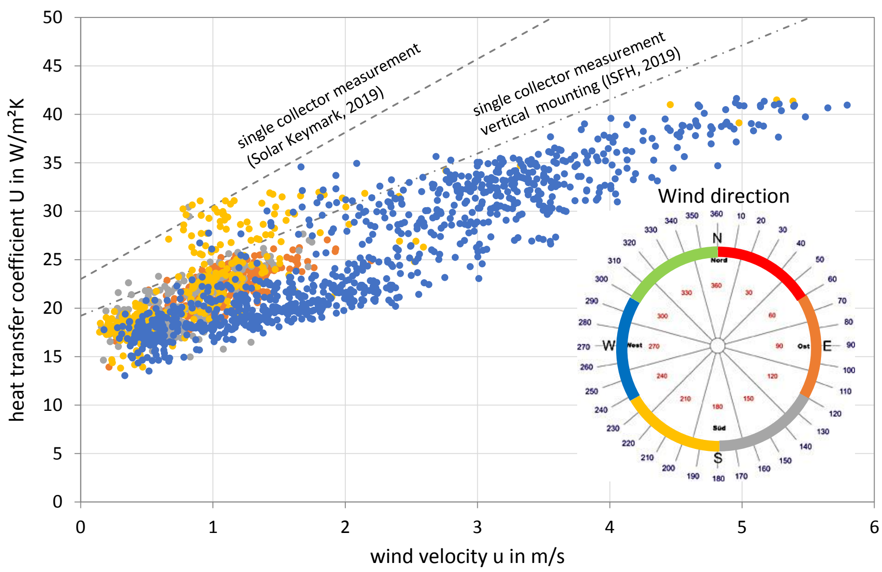


Figure 11: Heat transfer coefficient *U* of the PV-T collector field as a function of wind velocity *u* and wind direction (5-minute mean values)

The comparison between the field measurement and the heat transfer coefficient function $U = c_1 + c_3 \cdot u$ calculated with the collector parameters of the Solar Keymark test (s. Table 1) and the indoor test at ISFH for the vertical mounting configuration (s. Table 2) allows a first approximate quantification of the crucial role of the wind direction: at a wind velocity of 1.3 m/s the linear regression of the field data lies 30% lower than the Solar Keymark value but only 20% lower than the value for the vertical configuration. The restrictions on the comparability of indoor and outdoor measurements as well as the simplified character of the formula used to describe the heat transfer coefficient functions have to be taken into consideration for the evaluation. The residual deviation is assumed to be attributed to the different influencing factors mentioned above. A more precise differentiation and evaluation of all these factors cannot be carried out on the basis of the available data but require additional information from the ongoing field measurements under irradiation.

5. Conclusion and outlook

The investigated PV-T collector features a novel design provided with finned pipes, which significantly increase the area of the heat exchanger and enhance the convective heat transfer to (loss) or from (gain) the outdoor environment compared to state-of-the-art products. To analyze its thermal behavior as ambient heat exchanger for the use as low temperature heat pump source under real operation, we carried out measurements on large collector arrays at two different locations in Germany. For this purpose the measurement were performed during the night in the winter season.

The results have so far confirmed the unusually high heat transfer coefficient of the collector as well as its high sensitivity to the specific environmental and installation conditions. Both PV-T fields exhibit a *U*-value which is approximately 20 to 30 % lower than the *U*-value determined for the single PV-T module according to the standard performance test. This deviation can to a great extent be attributed to the different wind exposure during the measurements: on the one hand the small module is stronger affected by ventilation than the large field. On the other hand, due to the geometry of the heat exchanger fins, the PV-T collectors are particularly sensitive not only to the wind velocity but also to the wind direction. The tests at ISFH show that this field is predominantly flowed perpendicularly to the alignment of the heat exchanger fins, i.e under exposure conditions which impair the convective heat transfer. The presence of ice and the correspondent additional thermal resistance represents another influencing factor, which hasn't been analyzed during this measuring campaign.

The optional use of metal plates to close the gaps between the single PV-T modules and between the PV-T field and the roof significantly affects the rear ventilation of the field and the convective heat transfer mechanisms: for the investigated configuration we report a reduction of the *U*-value by about 30%.

The results generally confirmed the crucial role of the real installation and operation conditions on the performance of wind and infrared sensitive collectors (WISC), which can be neither described by the existing collector models nor detected by the test methods prescribed in the applicable Standards. For these collectors field investigations represent an essential complement to analyze and understand their behavior as well as to identify and exploit their optimization potential.

The ongoing tests address the PV-T field performance under solar irradiation and aim at a more comprehensive analysis of its behavior as well as at the definition of improved field configurations. Furthermore the impact of real operation, ice formation and deicing strategies on the thermal and electrical yield of the PV-T field will be assessed in the hardware-in-the-loop environment.

6. Acknowledgment

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