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Flat plate collectors with thermochromic absorber coatings to reduce loads during stagnation

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Abstract

Thermochromic absorber coatings, which switch their emissivity for thermal radiation depending on temperature, are developed to reduce the stagnation temperature of solar thermal collectors: In the operating range of the collector, the surface exhibits a low emissivity ($\varepsilon = 10\%$). At higher temperatures, the emissivity is increased by a multiple ($\varepsilon = 35\%$). Thus, the collector heat losses raise and the stagnation temperature is reduced. Efficiency measurements on a prototype collector employing this thermochromic absorber show, that below the switching temperature the efficiency is nearly identical to that of a conventional collector with a highly selective absorber plate. Due to the increased emissivity in the switched state of the coating, the stagnation temperature is lowered by more than 30 K. System simulations exhibit, that the performance of the system is not significantly affected: in a combined system for space heating and domestic hot water preparation the conventional energy demand of the gas boiler is increased by 1.5% to 4.5% using the thermochromic collector instead of a standard collector. In contrast, the duration when formation of vapour in the collector circuit occurs, is reduced by 70% to 75%. By further optimizing thermochromic collectors, the formation of vapour in the solar circuit could be completely prevented during stagnation. This would allow the use of lower cost materials in the solar circuit and reduce the cost of installation and maintenance of the solar circuit significantly.

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Keywords: thermochromic absorber coating; flat plate collector; stagnation temperature; system simulation; overheating protection

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1. Intoduction

Thermochromic absorber coatings have the particular feature, that their emissivity for thermal radiation is highly dependent on temperature: In the operating range of the collector below a predetermined switching temperature, the surface exhibits a low emissivity, comparable to that of commercially available highly selective absorbers (ε ≈ 6%). Above this switching temperature the emissivity increases by a multiple. Thus, the radiation heat transfer between absorber and glass cover increases significantly, the collector heat losses as well and the stagnation temperature is reduced.

The application of thermochromic absorber coatings enables a significant reduction of the temperature loads during stagnation on the collector and the solar circuit. Less temperature resistant materials can be employed to reduce costs of the collector and the entire solar thermal system. In addition, the avoidance of vapour formation in the solar circuit improves the operational safety of the system.

2. Development of thermochromic absorber coatings

In cooperation with partners from industry and research, suitable absorber coatings have been developed in several stages, extensively characterized and subjected to stress tests. A flat plate collector prototype was manufactured with absorber sheets that achieved the optical properties of conventional absorber coatings in the operating range (α ≈ 92%, ε ≈ 10%). Above the switching temperature, the emissivity increases to ε ≈ 35%. The coating-process was transferred from laboratory to an industrial scale successfully. The industrially produced large area coatings using the production site of Viessmann reach a high homogeneity regarding their optical properties. The optical properties shown in Figure 1 are measured data from an absorber plate, that was produced in typical collector size (approx. 2 x 1 m²).

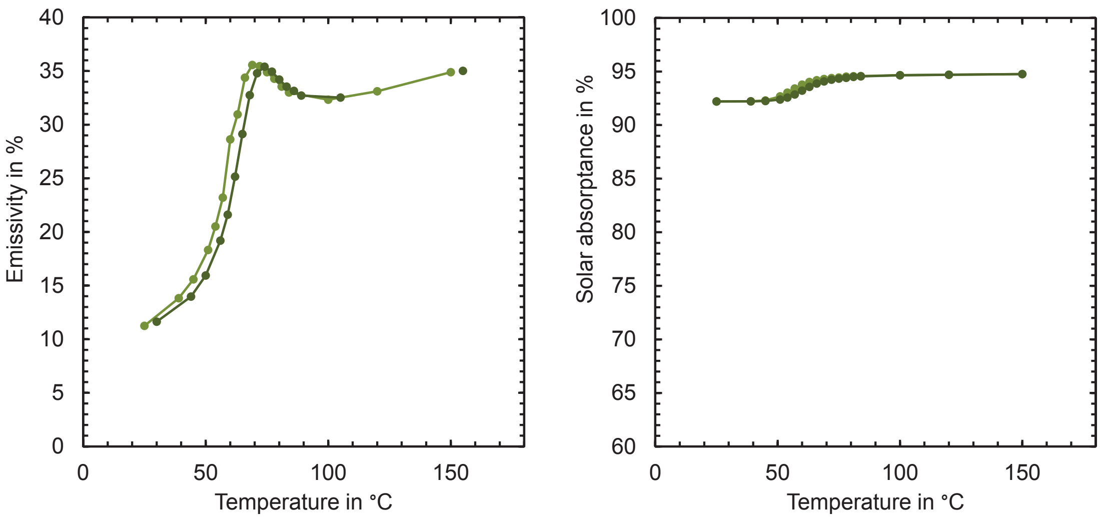

Fig. 1 Emissivity (left diagram) and solar absorptance depending on the surface-temperature for an industrially produced thermochromic coating in collector size (determined on the basis of spectral reflectance data measured at ISFH using Equinox 55 FTIR-spectrometer from Bruker equipped with a heating stage)

The switching-process of the thermochromic coating affects the emissivity within a temperature range from 55°C to 75°C. As both diagrams of Figure 1 indicate, there is a hysteresis in the thermochromic transition. The curve measured with increasing temperature is shifted by approximately +4 K against the one measured with decreasing temperature. The solar absorptance is affected by the thermochromic effect as well, but to a relatively small extent: It is increased from 92% to 94.5%, theoretically leading to higher temperature loads. However, this effect is negligible in relation to the effect of switching the emissivity. Further details regarding the coating development and its experimental characterization have been published by Mercs et al. [1].

The reliability of the new coating is extensively investigated in the laboratories of Viessmann, CEA INES and ISFH using various test methods. Stress testing by condensation at 40 °C have been successfully completed. First tests with ice at -10 °C and in the salt spray at 40 °C showed no abnormalities. In addition, a cyclic temperature load was applied with 7200 cycles between 40 °C and 140 °C, without causing degradation. This number of cycles corresponds to about a 20-year operation of the collector in a solar combi-system. For our investigations the test method for accelerated life testing of solar absorber layers developed in IEA SHC Task 10 and officially established as ISO 22975-3 [2] has been adjusted in accordance with the reduced temperature load on the thermochromic coating. The modified standard tests were successfully passed by the newly developed coatings.

3. Flat-plate collector prototype

With this new coating, a full-surface absorber was manufactured and integrated into a conventional flat plate collector housing. We carried out extensive efficiency measurements at ISFH on this collector and a collector with a standard absorber as a reference, both manufactured by Viessmann. As Figure 1 illustrates, the measured efficiency curve of the thermochromic collector below the switching temperature is almost at the same level as the characteristic of reference collector with a commercially available highly selective absorber plate. When the absorber temperature is above the switching temperature, the heat losses increase significantly, characterized by an increased gradient of the collector efficiency. As a result, the stagnation temperature (see Table 1) is reduced by more than 30 K compared with the standard collector, as measurements of the absorber temperature without artificial wind reported. These collector characteristics were confirmed by measurements in the sun simulator of CEA INES.

The absorber used was equipped with the first thermochromic coating produced in collector scale. Its optical characteristics are displayed in Figure 1. Optimized laboratory specimens with improved optical properties have been produced already, reaching an absorption rate of 94% and an emissivity, which switches from 6% to more than 40%. Both a higher efficiency in the operation range and a lower stagnation temperature of the collector can thus be expected by a successful transfer of this current development status to collector size.

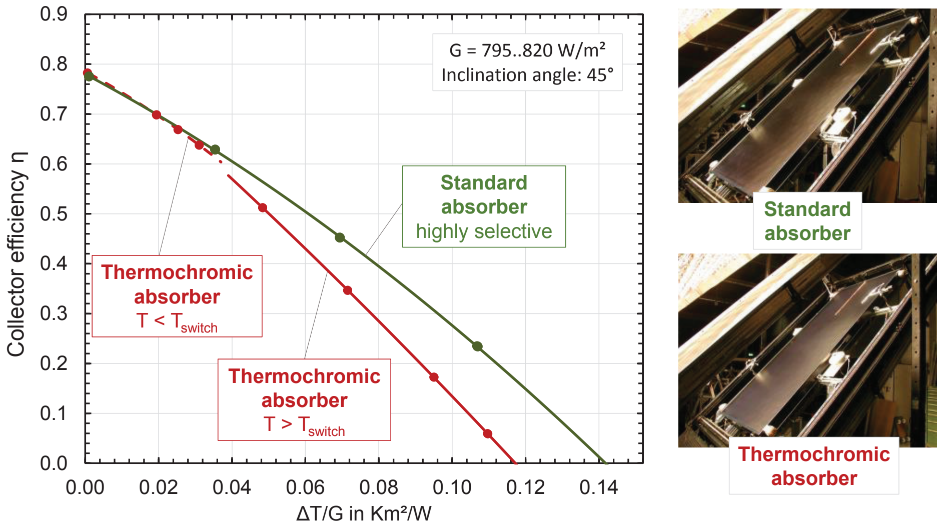

Fig. 2 Measured efficiency characteristics of the new flat plate collector prototype with a thermochromic absorber at temperatures below and above the switching temperature, compared to an identical collector with a common highly selective absorber coating.

Table 1 Measured results of the thermochromic collector compared to the standard collector. (Reason for the apparently higher conversion factor in the switched state is the piecewise fit method for determining parameters from measured data).

	Thermochromic collector		**Standard collector**
	$T < T_{switch}$	$T > T_{switch}$	
Efficiency parameters			
Conversion factor η_0	0.781	0.827	0.776
Heat loss coefficient a_1 in W/(mK²)	4.01	6.33	3.95
Heat loss coefficient a_2 in W/(m²K²)	0.032	0.009	0.013
Stagation temperature in °C			
(G = 1000 W/m², T_a = 30°C, without wind, 2/3 h_{abs})	-	164	195

4. System simulations

To investigate the effect of the temperature dependent efficiency parameters on the system behavior, we carried out dynamic system simulations in TRNSYS comparing the thermochromic collector with a standard collector featuring a conventional highly selective absorber.

An essential question is the influence of the reduced efficiency in the switched state on the system performance in operation, as the switching takes place within the operating range of the collector.

Further, the effect of the new absorber-coating on the temperature loads for collector and solar circuit, which occur in system operation, is examined. In addition to the maximum temperatures, the frequency distribution of the temperatures during stagnation plays an important role.

Within the system simulation setup a combined system with solar-assisted space heating (SH) and domestic hot water (DHW) preparation is examined in a single family house in TRNSYS [5]. For the simulations, the measured collector characteristics of the thermochromic collector and the standard collector, as presented in section 3, are used. The simulated system has been designed according to the constraints defined in Task 32 of the IEA SHC program. A detailed description of the system can be found in literature [3]. The simulations of the single family house with an effective floor area of 140 m² were performed with weather data from Potsdam [4], a typical location with temperate Central European climate, as well as weather data of Carcassonne, a site in the south of France with a comparatively high irradiation and high average ambient temperatures.

The collector array consists of seven collectors (aperture area 2.32 m² each, total aperture area of the field 16.24 m^2) and the buffer storage used has a volume of 750 l. In order to consider the influence of different user behavior, in addition to the reference case with an average daily DHW demand of 200 l/d (standard tapping profile according to [3]), variations with reduced DHW demand of 100 l/d, or 50 l/d were simulated. Furthermore, a two-week holiday period from 25th July to 7th August was considered, wherein no domestic hot water tappings take place.

The total energy demand of the system in Potsdam is dominated by the energy demand for space heating, even with a comparatively high DHW demand of 200 l/d, as Figure 3 shows. This applies even more to the case of reduced DHW demand. In contrast, with a DHW demand of 200 l/d, in Carcassonne 45 % of the total energy requirements are used for DHW preparation.

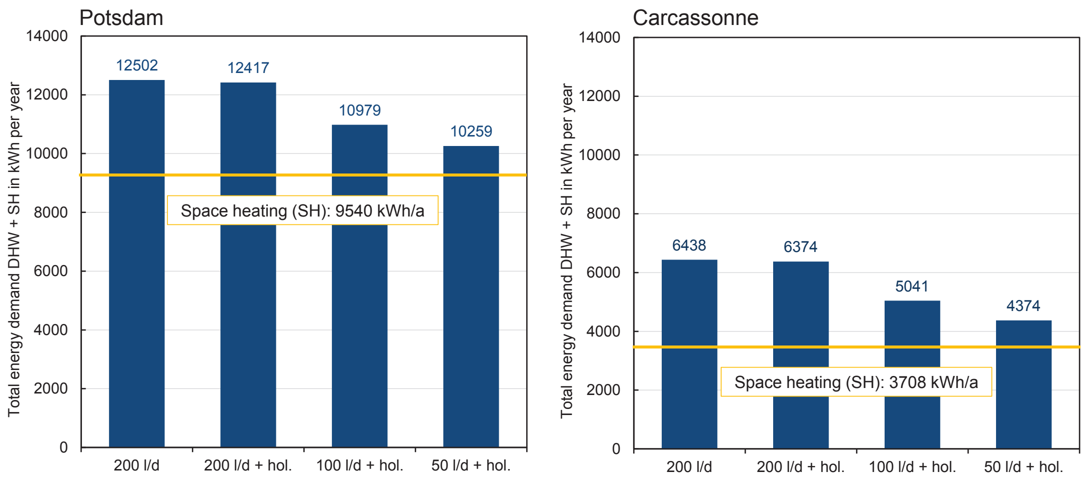

Fig. 3 Total energy requirement of the simulated system variants, split into space heating (SH) and domestic hot water portion (DHW) by the yellow line, for different average daily tapping volumes between 50 and 200 l/d, and the inclusion of a 2-week holiday period ("+ hol.") from 25th July to 7th August without DHW-tapping; left for the site of Potsdam, right for the location Carcassonne.

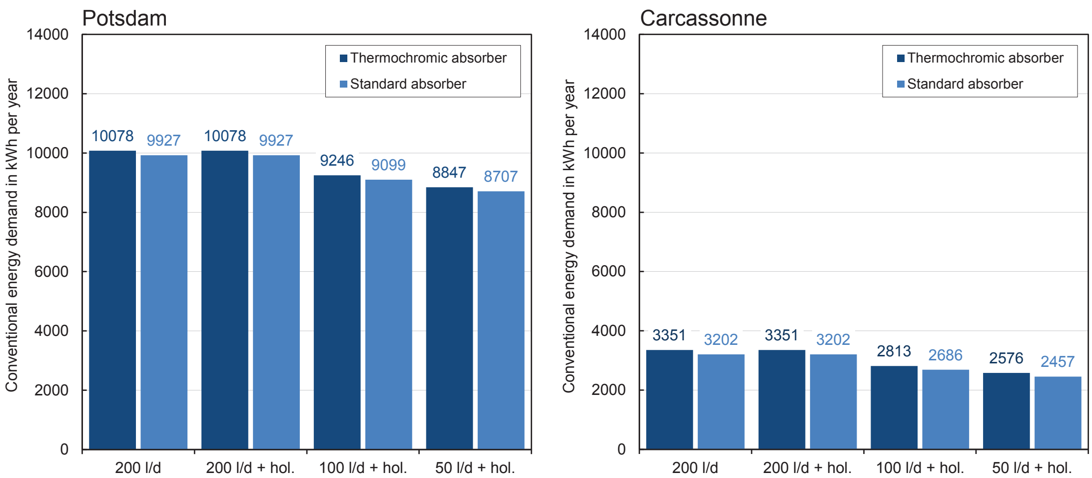

Fig. 4 Conventional energy provided by the gas boiler in kWh/a for different average daily tapping volumes between 50 and 200 l/d, and the inclusion of a 2-week holiday period ("+ hol.") from 25th July to 7th August without DHW-tapping; left for the site of Potsdam, right for the location Carcassonne.

In order to evaluate the performance of the thermochromic collector in comparison to the reference collector, the conventional energy demand, meaning the amount of energy provided by gas boiler, is considered (see. Figure 4). Thus, the conventionally provided final energy demand of the system is assessed, which is reduced by means of solar collectors. For Potsdam the conventional energy demand with the thermochromic collector is 140 kWh/a to 151 kWh/a higher (depending on the DHW demand) compared to the reference, which corresponds to a relative increase of 1.5%. For Carcassonne the conventional energy demand is increased by the thermochromic collector in a range of 119 kWh/a to 149 kWh/a, and thus about 4.5% above the reference case with the standard collector. It is to be noted that much smaller differences are to be expected for the thermochromic collector equipped with the new generation of improved thermochromic coatings, already existing on a laboratory scale.

The impact of the thermochromic coating on the maximum temperature in the collector is shown in Figure 5. The frequency distribution of the absorber temperature reveals, that the maximum occurring temperature is reduced by about 30 K for the same DHW demand, regardless of the location. In addition, the results show, that generally the occurrence of high temperatures, at which evaporation of the solar circuit fluid can take place, is significantly reduced. To evaluate the when the absorber reaches temperatures above 120°C and the collector circuit pump is turned off.

To evaluate the annual duration, when vapour formation in the solar circuit can occur, situations with switched off collector pump and temperatures above 120°C on the absorber plate are considered. This corresponds to the temperature at which common solar fluids, with a system pressure of 2 bar in the collector circuit, begin to evaporate. Figure 6 illustrates, that this "duration of vapour formation" is reduced by a factor of 1/3 to 1/4 employing the thermochromic collector instead of the standard one for both Potsdam and Carcassonne.

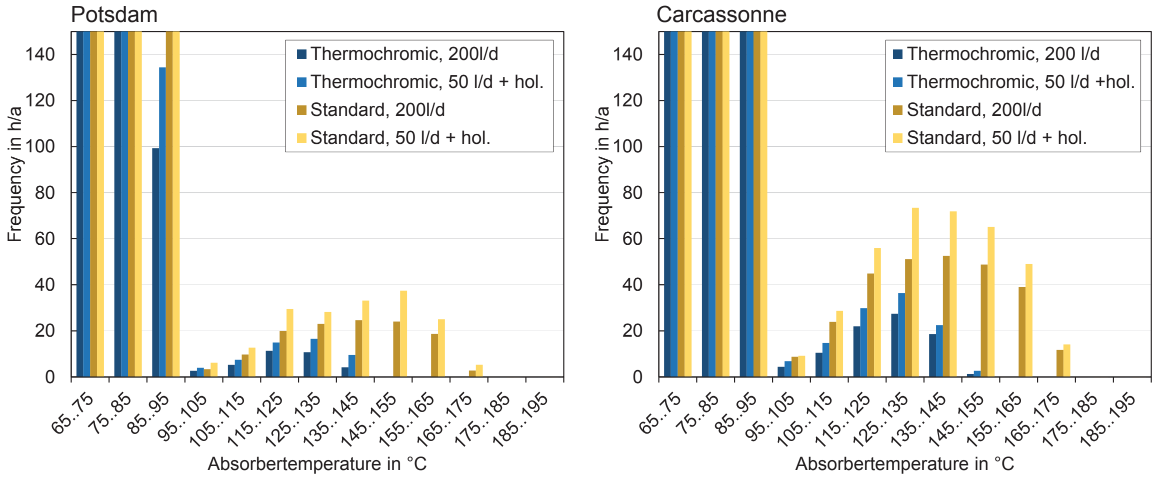

Fig. 5 Frequency distribution of the absorber temperature respectively for the lowest (50 l/d + hol) and the highest DHW demand (200 l/d) of the studied variations with the thermochromic absorber and the standard absorber; left for the site of Potsdam, right for the location Carcassonne.

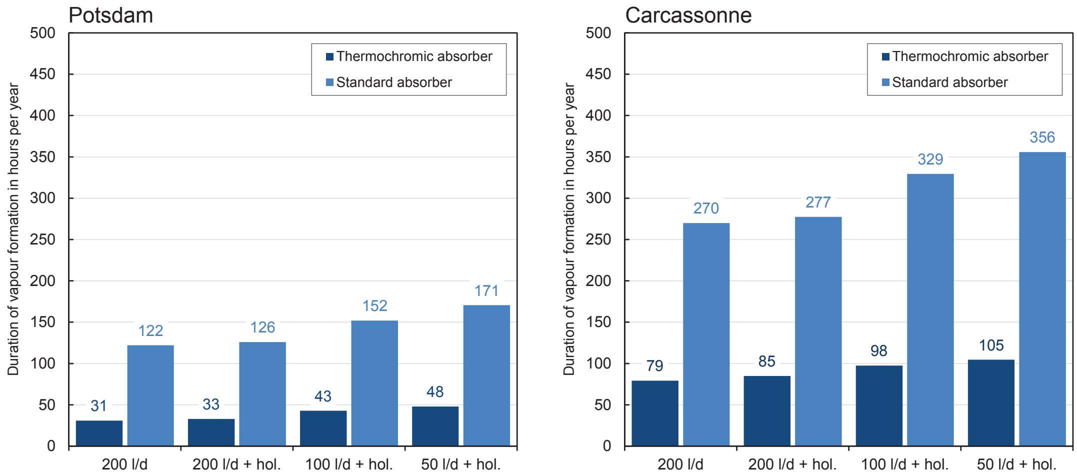

Fig. 6 Cumulated time in hours per year, in which evaporation in the solar circuit can occur ("duration of vapour formation") for different average daily DHW tapping volumes between 50 and 200 l/d and the inclusion of a 2-week holiday period ("+ hol.") from 25th July to 7th August without any tapping; left for the site of Potsdam, right for the location Carcassonne.

5. Conclusion

The paper describes the development of a thermochromic absorber coating that increases its emissivity depending on its temperature from 10% to more than 35%. This switching process takes place in a temperature range of 65°C ± 10°C. The novel absorber coating was successfully produced on an industrial scale, meeting the homogeneity requirements. The optimization of the switching behavior of the coating is currently in progress. According to the current state of development in laboratory scale, improved coatings can switch their emissivity from 6% to more than 40%.

Efficiency measurements on a prototype collector employing the first thermochromic absorber show that below the switching temperature, the efficiency is nearly identical to the one of a conventional collector with a highly selective absorber plate. Due to the increased emissivity in the switched state of the coating, the stagnation temperature is lowered by more than 30 K.

System simulations showed that, despite the relatively low switching temperature, which is within the collector operating range, the performance of the system is not influenced significantly: in the combined system the conventional energy demand covered by the gas boiler, is increased by 1.5% to 4.5% using the thermochromic collector instead of the standard collector. In contrast, the duration when the formation of vapour in the collector circuit occurs, is reduced by 70% to 75% and the maximum temperature in the collector is reduced by 30 K.

Avoiding the formation of vapour in the solar circuit offers great potential for the reduction of system costs. We pursue the goal to completely suppress the formation of vapour in the solar circuit by a further optimization of the thermochromic coating and a possibly accompanied increase in pressure in the solar circuit. Thus, the spread of the high temperature from the collector into the entire solar circuit could be prevented. This would allow the use of lower-cost materials in the solar circuit and would reduce the cost of installation and maintenance of the solar circuit significantly.

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