Flat Plate Collectors with Thermochromic Absorber Coating under Dynamic System Tests

Sebastian Müller[1], Rolf Reineke-Koch[1], Federico Giovannetti[1], Bernd Hafner[2]

[1] Institut für Solarenergieforschung Hameln (ISFH), Am Ohrberg 1, D-31860 Emmerthal (Germany),
Phone: +49 5151 999-646, E-Mail: mueller@isfh.de

[2] Viessmann Werke GmbH & Co. KG, Viessmannstraße 1, D-35108 Allendorf (Germany)

Abstract

Thermochromic absorber coatings switch their emissivity for long wave radiation depending on the absorber temperature. Below the specific switching temperature of 68 °C the coating's emittance is quite similar to a commercial, highly selective absorber coating ($\varepsilon \approx 5$ %). At higher absorber temperatures the emittance reaches $\varepsilon \approx 35$ %, whereby the collector heat losses increase. As a result, the stagnation temperature is reduced by 30 K and an overheating or vaporization of the heat transfer fluid can be entirely prevented. We have carried out collector performance measurements according to ISO 9806. By means of dynamic system tests (ISO 9459-5) we predict the performance of a domestic hot water system with standard and thermochromic collectors. At typical daily tapping rates the marginally lower absorptance of the thermochromic coating raises the auxiliary energy demand up to 2.5 % and reduces the solar fraction by about 1 %-absolute. In additional system stagnation tests, we analyzed the stagnation behavior of thermochromic collectors, especially the vaporization of the heat transfer fluid, the steam expansion into the solar pipes and the thermal stagnation load on sensitive solar loop components. A reduction of the stagnation period by 60 % and a limitation of the stagnation temperature to 145 °C were investigated.

Keywords: thermochromic absorber coating, flat plate collector, dynamic system testing, stagnation load

1. Introduction

The steady performance enhancement of solar flat plate collectors leads to higher thermal solar system gains but increases the temperatures in the whole solar loop as well. The stagnation temperature of standard flat plate collectors can easily reach up to 200 °C. Thus, temperature resistant and also cost intensive system components have to be used, to withstand the thermal stagnation loads and temperature distribution in the solar loop. Additional measures need to be taken, especially for larger thermal collector arrays or systems with short solar piping, to protect the whole system against thermal damages (e.g. degradation of heat transfer fluid), as Scheuren (2006) investigated.

Hausner et al. (2003) investigated the stagnation behavior in detail and characterized different collector types on the basis of their steam production performance. To prevent overheating and handle the stagnation loads, Harrison et al. (2012) and Frank et al. (2015) summarized different protective arrangements and stagnation control strategies. Föste et al. (2016a) developed different heat pipe collectors with reduced stagnation temperature and protection against vaporization of the heat transfer fluid. To reduce the stagnation loads in flat plate collectors, Brunold et al. (2007) suggested thermochromic layers as a potential method and Föste et al. (2016b) investigated industrially manufactured thermochromic flat plate collector models first. Drainback solar thermal systems can prevent any vaporization in the solar loop, as Botpaev 2016 summarized.

2. Thermochromic absorber coating

Thermochromic absorber coatings have a highly temperature dependent emissivity for thermal radiation. This innovative smart selective coating increases its emittance ε above a predetermined "switching point" ($T_S \approx 68$ °C

doi:10.18086/swc.2017.31.10 Available at http://proceedings.ises.org

absorber temperature) from 5 % up to 35 %. The increase of the emittance above T_S can be explained as a first-order phase transition, which changes the internal crystalline structure in the thermochromic layer. The electronic band structure is altering from a semi-conductive to metallic character, whereby the electrical conductivity increases and influences the emittance. Pazidis et al. (2015) and Mercs et al. (2016) investigated, that this "switching" is a fully reversible process, as can be seen in Figure 1.a, as well as the long-term stability with accelerated aging tests. The layer stack on aluminum substrate consists of the active vanadium dioxide (VO_2) layer with an antireflective coating (SiO_2) on top (Figure 1.b).

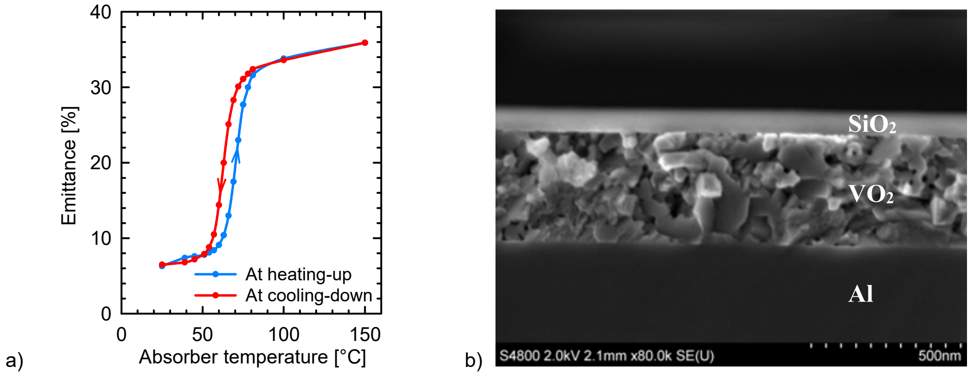
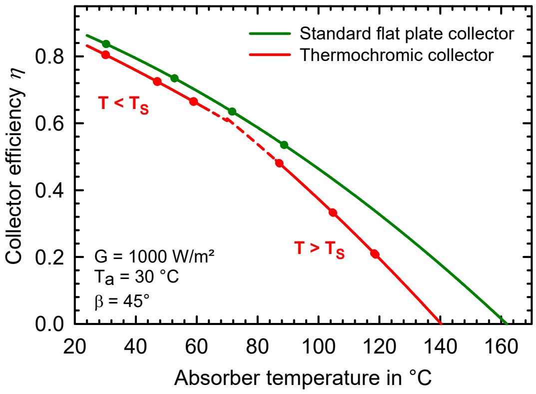


Fig. 1: Temperature dependent, fully reversible switching of emittance (a) and SEM cross section of absorber coating (b)

The thermochromic collector's behavior in the typical operating range is quite similar to a standard flat plate collector with a commercially available highly selective absorber coating ($\alpha > 94$ %, $\varepsilon \approx 5$ %). But in the switched state, the heat losses from the absorber to the glass cover increase significantly. Hence, the stagnation temperature is reduced by 30 K, the vaporization of the heat transfer fluid could be prevented more easily and the thermal stress for sensitive solar loop components (e.g. solar pump or membrane expansion vessel) could be lowered. Because of the reduction of thermal loads during stagnation, the components in typical solar thermal applications can be re-dimensioned or substituted to reduce the specific system costs and maintenance efforts.

3. Collector efficiency measurement

We have carried out collector performance measurements on an industrially manufactured thermochromic flat plate collector according to ISO 9806 (2013). Due to the fact, that our innovative coating changes its characteristic after the switching point with temperature T_S, the collector efficiency curve is splitted in two sections: the first describes the efficiency below the switching temperature and the second is valid for temperatures above T_S, both with their explicit collector efficiency parameters η_0, a_1 and a_2. For the evaluation we measured stationary collector efficiencies at three different absorber temperatures in each section as shown in Figure 2.



	$\eta_{0,Ap}$ -	a_1 W m^{-2} K^{-1}	a_2 W m^{-2} K^{-2}
Standard collector	0.786	4.19	0.0135
$T < T_S$	0.757	4.27	0.0065
$T > T_S$	0.830	6.17	0.0103

Fig. 2: Collector efficiency curves of a thermochromic and a standard flat plate collector related to their absorber temperature

Due to a marginally lower absorptance of the thermochromic absorber coating, the conversion factor η_0 is 3 %-absolute lower compared to an identically designed standard flat plate collector (η_0 = 0,786, related to aperture area). The characteristic in the un-switched state is otherwise comparable to that of a standard collector. The higher emittance and heat losses at temperatures above T_S reduce the collector efficiency, which can be expressed in the gain of the linear heat loss coefficient a_1 from 4.27 to 6.17 W m^{-2} K^{-1}. Thus, the stagnation temperature was measured to 167 °C, 25 K lower compared to a standard flat plate collector (192 °C).

The splitted collector efficiency curve represents its characteristic sufficiently accurate. In system simulations with TRNSYS, the collector efficiency parameters switch instantaneously (without any hysteresis (cf. Fig. 1.a)), if the absorber temperature exceeds the temperature T_S. In the Solar Keymark certificate both curve sections are displayed as well as the "mixed" curve, which includes all measured stationary points. The annual collector outputs at mean fluid temperatures of 25 °C and 50 °C are calculated with the lower ($T < T_S$) efficiency parameters.

4. Experimental system yield prediction

4.1 Dynamic system testing

For an experimental performance assessment of the innovative selective absorber coating, we carried out dynamic system testing (DST) according to ISO 9459-5 (2007) on a solar domestic hot water (SDHW) system equipped with thermochromic collectors. The DST describes a dynamic short term measurement method for the evaluation of a SDHW system within 3…4 weeks, without testing each component by its own and no requirements of steady-state conditions. To acquire sufficient measurement data, the system operates in three different test sequences predefined by the standardization, to identify the thermal behavior of a SDHW system by pursuing it in all its relevant states. There is no need of measuring internal quantities, why this method is also compared with a "black box" approach. So only eight external quantities (e.g. irradiance, auxiliary energy demand, temperature of domestic hot water, wind velocity) have to be measured meanwhile as a function of time.

Mathematically, the whole system is described by seven system specific parameters, which have to be identified on the basis of measured data by dynamic fitting (DF) algorithm. The software minimizes the difference between measured and simulated system performance of the implemented physical SDHW system model. This physical model and the software DF are described by Visser and Pauschinger (1997) and Spirkl (1997), respectively. A long term performance (LTP) prediction of the annual solar system gain, auxiliary energy demand and solar fraction can be calculated with the mentioned short term test procedure from the identified parameters under arbitrary weather conditions.

The two SDHW systems were installed on an outdoor testing roof. The thermochromic system is compared to an identical solar thermal system equipped with standard collectors. Both systems have a gross area of 5 m² (2 collectors per array) each and a domestic hot water tank with a volume of 300 liters. An electrical immersed heater with a power of 6 kW is used for providing the auxiliary energy demand. The collector arrays are sloped by 38° and faced to south. The measurement and the investigations are carried out synchronously under the same environmental conditions, so that the systems can be compared directly with each other.

4.2 Evaluation and long term prediction

The identified system parameters (by DF) represent basically a combination of several physical phenomena, interactions between system components and even neglected effects. However, according to Spirkl (1992) it is possible to interpret some of them as real physical parameters, referring directly to a system component. Therefore U_S, C_S and f_{Aux} describe the total hot water tank heat loss rate, the thermal capacity and the share of store volume heated up with the immersed heater. The auxiliary parameters D_L and S_C characterize the mixing effects during hot water tapping and the SDHW tank stratification while storage charging, respectively. A_C* and u_C* are related to the collector area and its overall heat loss coefficient and describe mathematically the whole solar loop.

The parameters identified by the synchronous DST measurement are shown in Table 1. Due to the marginally worse optical properties of the thermochromic layer, as mentioned in chapter 3, the identified effective collector area A_C* of the thermochromic system is 3.4 % smaller than the standard collector one. The rising collector heat losses in the switched state are responsible for the higher u_C* of the thermochromic collector. Some other identified system parameters can be compared with measured data as well. For example the total heat loss rate of the SDHW tank U_S amounts to 2.2 W K^{-1} and the thermal capacity C_S to 1.25 MJ K^{-1}. According to manufacturer's data sheet of the installed SDHW tank, the share of auxiliary heated volume f_{Aux} should be 0.44. The identified D_L value of almost 0 is equal to no mixing during draw-off, which can be expected for this kind of bivalent SDHW tank.

Tab. 1: System specific parameters identified by the DF alogrithm

Parameter	**A_C*** **m²**	**u_C*** **W m^{-2} K^{-1}**	**U_S** **W K^{-1}**	**C_S** **MJ K^{-1}**	**f_{Aux}** **-**	**D_L ¹⁾** **-**	**S_C ²⁾** **-**
Standard collector system	2.96	10.16	2.44	1.27	0.54	0.018	0.042
Thermochromic collector system	2.86	10.55	2.33	1.28	0.55	0.017	0.034

¹⁾ $D_L = 0$ is equal to no mixing during draw off
²⁾ $S_C = 0$ is equal to a solar heat exchanger, immersed at the bottom

For the LTP prediction of the system performance the predefined boundary conditions in ISO 9459-5 (2007) were used, with a draw-off temperature of 45 °C, an auxiliary set-point temperature of 60 °C and an ambient store temperature of 15 °C. The weather data for the four reference locations (Athens, Davos, Stockholm, Würzburg) given in the Standard were substituted by data from Meteonorm 7 (2012), due to comparability with system simulations done in TRNSYS.

The system performance is assessed by the auxiliary energy demand Q_{Aux}, which is provided by the immersed electrical heater into the SDHW tank in addition to the solar thermal gain to cover the domestic hot water energy demand Q_{DHW}. For this kind of investigation and system comparison it is the most meaningful parameter, because an increase of Q_{Aux} due to the installation of thermochromic instead of standard flat plate collectors leads to higher annual costs for the operator. At the reference location of Würzburg, the increase of auxiliary energy demand is less than 2.5 % over a wide range of daily tapping rates as shown in Figure 3. This is equal to 33 kWh a^{-1} at a daily tapping rate of 140 liters. At the other locations we predicted qualitatively the same increase of Q_{Aux} with maximum values of 5.6 % (Davos), 5.1 % (Athens) and 1.7 % (Stockholm).

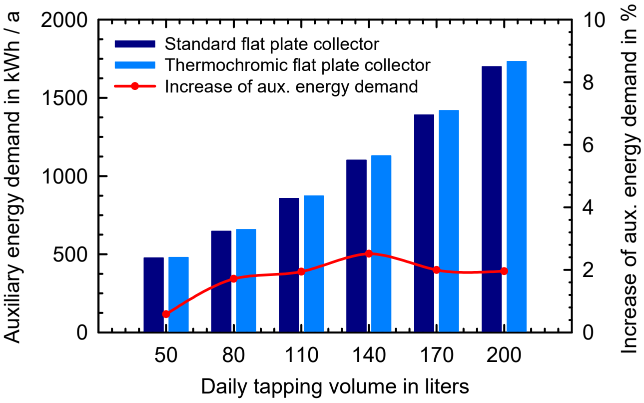


Fig. 3: Auxiliary energy demand for the thermochromic and standard SDHW system at the reference location of Würzburg

The solar fraction of a SDHW system characterizes the share of solar thermal gain into the SDHW tank, related to the domestic hot water energy demand Q_{DHW}. Furthermore and in reference to the Standard, the thermal gain can be expressed as the difference between the load energy Q_L and auxiliary energy demand Q_{Aux}.

$$f_{Sol} = \frac{Q_L - Q_{Aux}}{Q_{DHW}} \qquad (eq.1)$$

Figure 4 shows the solar fraction for all four reference locations over a wide range of daily tapping volumes (50…600 liters per day). At Würzburg, the f_{Sol} of the standard SDHW system reaches its maximum of 47.5 % at daily tapping rates of 110 liters and decreases for lower and higher tapping rates. These are typical values for this combination of collector gross area and SDHW tank volume. The SDHW system with thermochromic collectors exhibits qualitatively the same characteristic, but the solar fraction is 1 %-absolute lower than the standard system. The difference in solar fraction is nearly independent from the daily tapping rate. So it can be assumed, that the difference in system performance depends primarily on the slightly worse optical properties of the thermochromic coating as on the increased thermal losses in the switched state.

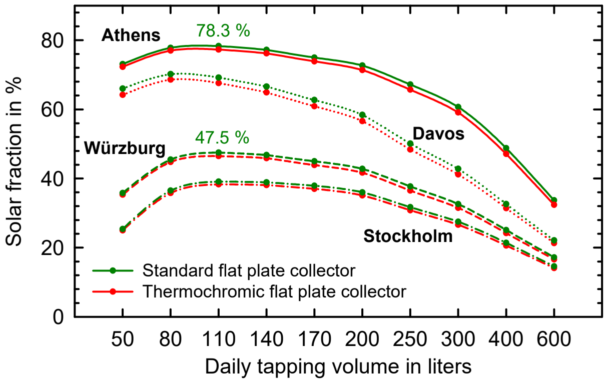


Fig. 4: Solar fraction for all four reference locations, variation of daily tapping volume and measured SDHW systems

Similar results are achieved considering the other reference locations. The mean difference in f_{Sol} over the whole range of tapping rates can be assessed to 1.2 (Athens), 1.6 (Davos) and 0.9 (Stockholm) %-absolute.

4.3 Cross-check with TRNSYS replica

To check the plausibility of the DST procedure and especially the LTP of the annual thermal system gain, we carried out system simulations with the software TRNSYS. Furthermore, a cross-check for the use of the implemented collector model with thermochromic collectors was investigated, as well. Thus, the installed SDHW system was modelled in TRNSYS in detail, considering all system parameters, e.g. length of solar piping, collector gross area, heat loss rate of SDHW tank, auxiliary power, etc. (cf. chapter 4.2). Even the matched flow operation mode was implemented into the system controller. The SDHW tapping was adjusted to the requirements of the Standard (one tapping per day; tapping rate 10 liters per minute; six hours after solar noon).

The comparison between the system simulations with the TRNSYS SDHW-replica and the DST long-term performance prediction was assessed by considering the solar fraction and the auxiliary energy demand again. The solar fraction of the thermochromic collector at the reference location of Würzburg can be modelled with an accuracy of less than 2 %-absolute within a wide range of daily tapping volumes (50…600 liters per day). As can be seen in Figure 5.a, within the range of 140…600 liters per day the difference decreases to less than 1 %-absolute. The auxiliary energy demand (see Figure 5.b) reports maximum differences of 3.1 %. For typical daily tapping rates (80…170 liters per day) the deviation does not exceed 1.5 %.

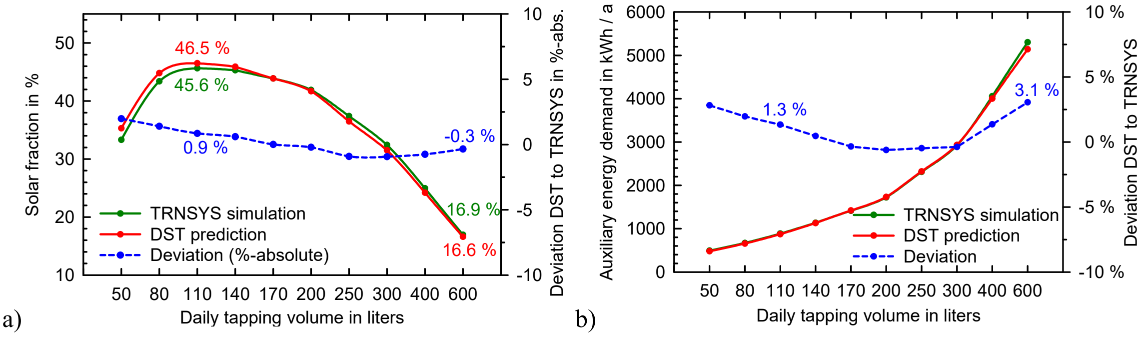


Fig. 5: Comparison of solar fraction (a) and auxiliary energy demand (b) for a system with thermochromic collectors between TRNSYS simulation and DST long-term performance prediction

For the standard collector array, we achieve similar results. Over the whole range of daily tapping rates, the auxiliary energy demand and the solar fraction are simulated with deviations of less than 5 % and 3.5 %-absolute, respectively compared to the DST long-term prediction.

The evaluation was carried out for the other three reference locations as well. The results for Athens are similar to those for Würzburg. At Stockholm, the deviations between simulation and DST prediction are marginally lower, with maximum differences in auxiliary energy demand and solar fraction of 1.8 % and 1.4 %-absolute, respectively. The solar fraction at Davos can be modelled within 2.8 %-absolute and the auxiliary energy demand with deviations less than 6 %.

The results of our TRNSYS simulations with both SDHW systems confirm the DST long-term performance prediction as well as the applicability of the DST method to thermochromic flat plate collectors.

5. Stagnation tests

Pazidis et al. (2015) reported in a previous simulative study, that a thermochromic SDHW system could lower the stagnation time (here: timespan, in which the absorber temperature is above 120 °C) by more than 70 %. According to the simulation results, the maximum absorber temperature under normal operating and environmental conditions can be limited to 145 °C (Würzburg). To verify these investigations and experimentally evaluate the stagnation behavior of thermochromic collectors, we have carried out additional stagnation tests to analyze the steam expansion in the solar pipes due to the vaporization of the heat transfer fluid, the stagnation load on the collector itself and the temperature distribution in the whole solar loop. We focused especially on the thermal load on sensitive components, like the membrane expansion vessel or solar pump. An increase of the system pressure will be investigated in detail to raise the saturated steam temperature of the heat transfer fluid and prevent vaporization in the solar collector.

5.1 Experimental setting

We used both SDHW systems for our investigations, with the specifications mentioned in chapter 4.2 (see Figure 6.a). The overall solar loop length is 30 m per system to measure the steam expansion in detail, which is the most representative indicator for stagnation loads. Therefore, we installed temperature sensors (Pt1000) directly onto the solar piping, starting from the collector in- and outlet at intervals of 1.5 meters. The temperature distribution in the collector array is measured with four sensors at each absorber. Some more sensors were installed to quantify the thermal load on the solar pump and the membrane expansion vessel. One pressure sensor was added at the collector array outlet to investigate the stagnation dynamics and possible hydraulic shocks during stagnation. All sensors and their positions are displayed in the hydraulic schema in Figure 6.b.

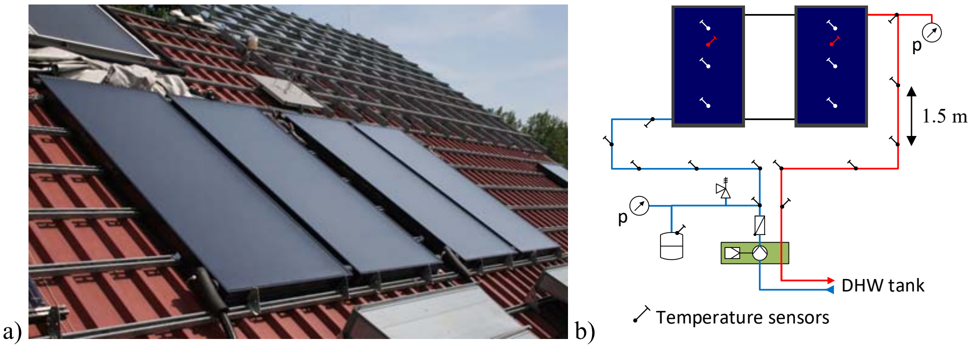


Fig. 6: Investigated SDHW collector arrays on the outdoor testing roof (a) and hydraulic schema with temperature and pressure sensor positions

The survey started in late 2016. During the tests the two systems were operated synchronously under well-defined stagnation conditions. We detected eight stagnation events, whereof four days under clear sky conditions. On these four representative days, the system operated at three different relative system pressures (2.0 bar, 2.2 bar, 3.2 bar). On one of these days, a so called “noon stagnation” was manually performed, by switching off the solar pump only at solar noon.

5.2 Evaluation of representative days

Maximum absorber temperatures occur usually at two-third of collector’s height. Figure 7.a compares these temperatures for the thermochromic and the standard flat plate collector at three different relative system pressures. The stagnation temperature of a collector is independent from its system pressure. Due to higher heat losses, the stagnation temperature of the thermochromic collector is limited to 145 °C under natural conditions (including wind). Hence, we report a reduction of 30 K.

If the absorber temperature exceeds at any position in the collector array the saturated steam temperature of the used heat transfer fluid (TYFOCOR LS) at the specific relative system pressure, the fluid starts to vaporize. The saturated steam temperatures for the three investigated system pressures 2.0 bar, 2.2 bar and 3.2 bar are 139 °C, 141 °C and 150 °C, respectively. The steam expands into the solar pipe with increasing steam volume. We could detect the steam front, by comparing the pipe temperature recorded by the sensors to the current saturated steam temperature. The start of the fluid vaporization is attended by a soaring temperature at the collector outlet, as displayed in Figure 7.b. If the temperature at the collector outlet falls below the saturated steam temperature, the vapor condensates completely and no steam fills the solar piping anymore.

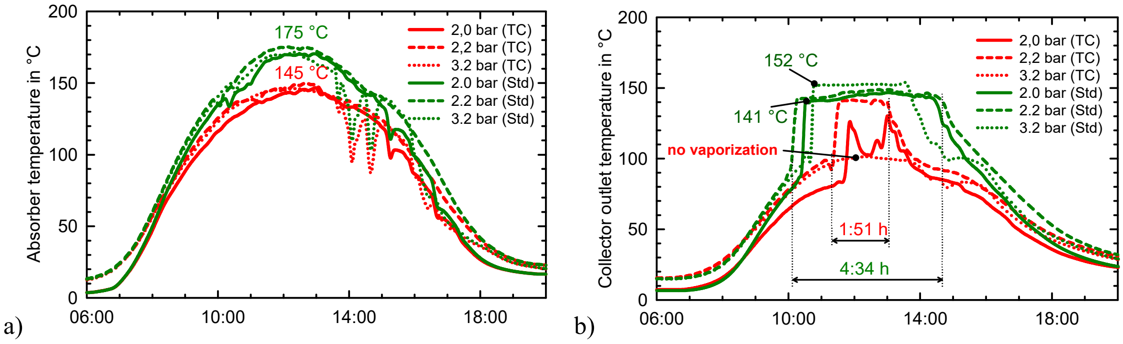


Fig. 7: Absorber temperature of thermochromic (TC) and Standard (Std) collector at two-third of the collector's height (a) and collector array outlet temperatures (b) for various relative system pressures

We define "stagnation period" as the timespan between the start of vaporization and the time, at which the entire system is free from steam again. For the evaluation with a system pressure of 2.2 bar, the stagnation period is reduced by 60 %, from 4:34 hours (standard collector array) to 1:51 hours. At 2.0 bar the stagnation period could be halved. The entire vaporization could be prevented at system pressures higher than 3.2 bar (see Figure 7.b). In this case, no steam expands into the pipes and the thermal load and the temperature distribution in the solar loop could be significantly lowered. The maximum outlet temperature is reduced from 154 °C in the standard collector array to 102 °C in the thermochromic collectors.

Insufficient data acquisition for the evaluated period in 2016, with a few stagnation events only, could not represent the stagnation behavior of both SDHW systems in detail. We will carry out the measurement and double the collector area in addition. To investigate the stagnation dynamic and the draining behavior more in detail, a high frequency pressure measurement at collector array outlet is planned. For further investigations, we calibrated both membrane expansion vessels to determine the whole steam volume in the collector loop only by measuring its fluid inlet temperature and the system pressure at the expansion vessel. This method was developed and introduced by Scheuren (2008). With the system steam volume and qualitative measured steam expansion, an evaluation of residual fluid and draining behavior is feasible.

6. Conclusions and outlook

By means of synchronous dynamic system tests according to ISO 9459-5 we predicted and compared the long-term performance of SDHW systems equipped with thermochromic and standard flat plate collectors. Our results confirm the high performance of a SDHW thermochromic system. The increase of auxiliary energy demand, by installing thermochromic instead of standard collectors, is less than 2.5 % for daily tapping rates between 50 and 600 liters at the reference location of Würzburg. Even for the warmer reference location Athens, the gain in auxiliary energy demand does not exceed 5.1 %. The low increase in auxiliary energy demand and the marginally low difference in solar fraction over a wide range of daily tapping volumes and locations reveal, that the slightly worse optical properties of the thermochromic collector influence the system performance more than the higher heat losses in the switched state.

On the basis of system simulations with TRNSYS, we could cross-check the DST long-term performance prediction and confirm the applicability of the implemented DST collector model on thermochromic flat plate collectors. We assume that the dynamic short-term measurement method can be extended to all kind of collectors with unsteady efficiency behavior, e.g. collectors with thermally actuated ventilation door (cf. Frank 2015) or heat pipe collectors (cf. Föste 2016a). The results confirm the high performance of the thermochromic collectors in a SDHW system, which is comparable to that of a standard collector.

The stagnation behavior was analyzed by additional experimental stagnation tests. We report a limitation of the stagnation temperature at 145 °C and, thus, a reduction of 30 K compared to a standard flat plate collector. The stagnation period – the timespan, in which any steam is detected in solar thermal system – could be reduced during the measurement up to 60 % at normal system pressures. The vaporization can be entirely prevented by a slight pressure rise, which offers great potential for further reduction of system costs. We assume a significant reduction in installation and maintenance costs or the use of cost-effective (not high temperature-resistant) materials by avoiding vaporization and therefore less thermal loads for the whole system.

The thermochromic coating is currently under further development, with the aim to improve its optical properties and extend its temperature operating range. The main goals are the increase of the solar absorptance (α > 95 %), as well as the thermal emittance in switched state (up to 60 %) and a shift of the switching temperature T_S to 80 °C. We expect a gain in collector performance and a further reduction of the stagnation temperature at once.

Acknowledgement

The project “Process technology, quality assessment and system solutions for thermochromic absorbers in solar thermal collectors” presented in this paper is funded by the German Federal Ministry of Economic Affairs and Energy based on a decision of the German Federal Parliament (reference numbers 0325858 A and B). The project ProTASK is carried out in cooperation with Viessmann Werke GmbH & Co. KG.

The authors are grateful for the financial support and responsible for the paper’s content.

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