Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 48 (2014) 48 – 57

Energy Procedia

SHC 2013, International Conference on Solar Heating and Cooling for Buildings and Industry
September 23-25, 2013, Freiburg, Germany

Performance and reliability of a high efficiency flat plate collector – final results on prototypes

Sebastian Föste[a]*, Federico Giovannetti[a], Nicole Ehrmann[a], Gunter Rockendorf[a]

[a]*Institut für Solarenergieforschung Hameln (ISFH), Am Ohrberg 1, 31860 Emmerthal, Germany*

Abstract

The paper presents the final results of our prototype investigations regarding the performance and reliability of a high efficiency flat plate collector with a gas-filled low-e double-glazing as transparent cover. The measured efficiency of an optimized prototype results in an increase in efficiency of 70 % at a temperature difference of 60 K (G = 500 W/m²) compared to a standard flat plate collector. The effect of additional antireflecting coatings and different gas fillings of the glazing is analyzed by prototype measurements. As the heat losses of the collector are significantly reduced by the low-e glazing, a stagnation temperature of 265 °C was determined at the absorber plate experimentally. The collector components have to withstand these increased temperature loads. Test and assessment methods for the long term stability of the hermetically sealed double-glazing against high temperatures and the combination of temperature and UV-radiation were developed and performed successfully. Further, the reliability of four prototype collectors was confirmed by a one-year outdoor-exposure test. A simplified economic analysis resulted in an optimum operating range for the collector of 80 °C to 110 °C compared to commercially available flat plate and evacuated tube collectors. As the main result of the research project, a new flat plate collector with a significantly increased performance and an experimentally proved reliability was developed up to a prototype status, which can be transferred to industrial production.

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG

Keywords: flat plate collector; low emitting coating; low-e; collector efficiency; indium tin oxide; aluminum zinc oxide

* Corresponding author. Tel.:+49 5151 999 505; fax: +49 5151 999 505.
E-mail address: foeste@isfh.de

Selection and peer review by the scientific conference committee of SHC 2013 under responsibility of PSE AG
doi:10.1016/j.egypro.2014.02.007

1. Collector concept

The aim of our research project is to develop a new high efficiency flat plate collector up to a prototype status. The general concept of this collector, as shown in Figure 1, is the combination of a standard flat plate collector and a low-e[1] double-glazing. As these two components are standard industrial products, the fabrication of this collector can be highly automated, which provides benefits for the expected production costs. The key component of the collector is the high-transmittive low-e coating on position 3 of the glazing (see Figure 1). For the collector application a high transmittance in the solar wavelength range (300 – 2500 nm) is essential. In cooperation with the glass manufacturing company Euroglas GmbH, suitable low-e coatings based on transparent conductive oxides were developed on glass panes in collector size. Two different materials for the functional layer were tested: aluminum zinc oxide (AZO) and indium tin oxide (ITO).

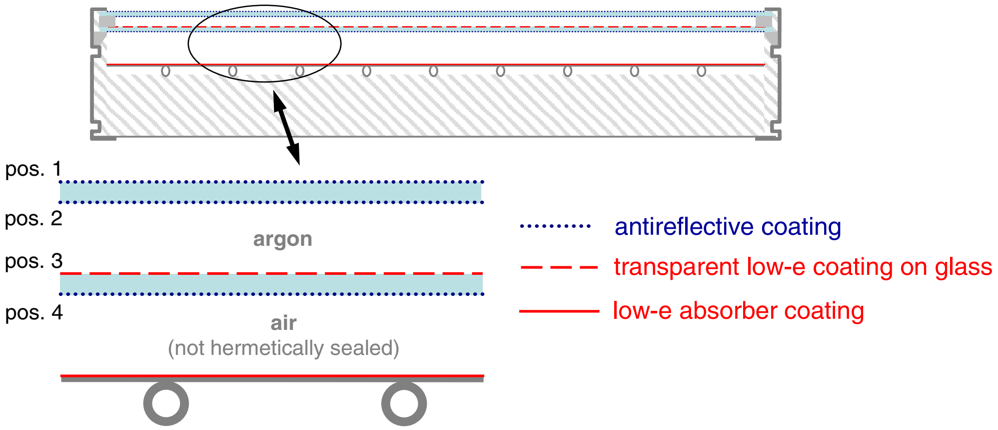

Fig. 1. Concept of the high efficiency flat plate collector with a low-e coated double-glazing.

Nomenclature

a_1	linear heat loss coefficient according to EN 12975-2 [3] in W/(m²K)
a_2	quadratic heat loss coefficient according to EN 12975-2 [3] in W/(m²K²)
a_{60}	effective heat loss coefficient at ΔT = 60 K
b_0	coefficient of incidence angle modifier according to EN 12975-2 [3]
$f_{sav,ext}$	fractional energy savings according to [9] in %
G	global irradiance in W/m²
T_{amb}	ambient air temperature in °C
ΔT	temperature difference between mean fluid temperature and ambient air temperature in K
η	collector efficiency
η_0	conversion factor according to EN 12975-2 [3]
$\eta_{0.06}$	collector efficiency at $\Delta T/G$ = 0.06 Km²/W
λ	wavelength of solar radiation in nm

[1] Low-e stands for „low emissivity“, which means that the outer glass surface (pos. 3) of the inner glass-pane is equipped with a spectrally selective coating, which emits low levels of thermal energy and thereby reduces the heat transfer by radiation in the gap between the two glass panes.

2. Design parameters and collector performance

We built a prototype collector with an indium tin oxide (ITO) low-e coating applied in the argon-filled glazing. The lower glass pane with a low iron content and coated on one side with the ITO coating system provides a solar transmittance (λ = 300 – 2500 nm) of 86.5 %. If an additional antireflective coating on the opposite side of the glass pane is applied, the solar transmittance is increased to 89 %. The low-e coating reduces the thermal emissivity from 83 % (uncoated glass) to 30 %.

The gap sizes between the absorber and the glass panes are dimensioned to minimize convective heat losses depending on the used gas filling according to previous theoretical and experimental investigations [1].

As the front side heat losses of the collector are significantly reduced by the low-e double-glazing, the backside heat losses through the opaque insulation become more important. A detailed study based on experimental data and calculations with a validated collector model [2] was performed to investigate the impact of the backside insulation on the collector performance. As a result of this study, we recommend an enhanced thickness of the backside insulation of 80 mm (mineral wool). In conventional single glazed flat plate collectors, thicknesses between 40 mm and 50 mm are usual.

Performance measurements were carried out according to EN 12975-2 [3] using the ISFH sun simulator under stationary conditions. To compensate spectral deviations between the sun simulator irradiance and natural irradiance the conversion factor η_0 is measured using the solar tracker as shown in Figure 2. Depending on the number of antireflective coated glass surfaces used in the collector glazing, conversion factors η_0 between 0.780 and 0.799 are achieved, which are comparable to standard single-glazed flat plate collectors (FPC). Due to the significantly lower front side heat losses, the collector efficiency at a temperature difference between fluid and ambient air of 60 K is increased by approximately 70 % (global irradiance G = 500 W/m²) compared to the standard FPC. The incidence angle modifier (IAM) is measured at stationary incidence angles of 0°, 40° 50° and 60° with the solar tracker. According to the IAM definition of the EN 12975-2 [3], a coefficient b_0 = 0.18 was determined.

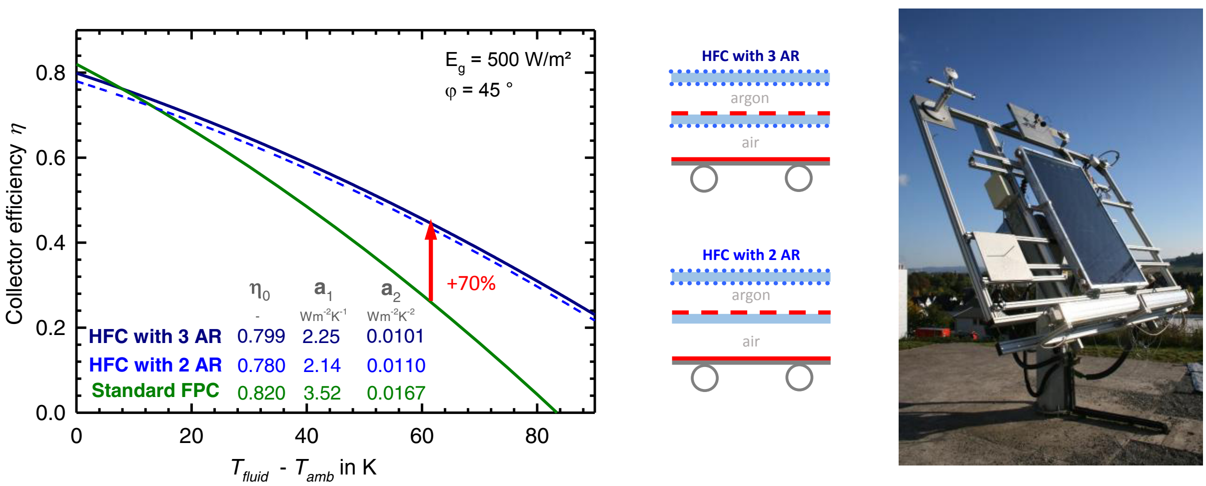

Fig. 2. Measured efficiency curves of the high efficiency flat plate collector with two ("HFC with 2 AR") and three antireflective coatings ("HFC with 3 AR") compared to a single-glazed flat plate collector ("Standard FPC").

To investigate the influence of the gas filling on the heat losses, collector measurements with krypton and air were carried out. The krypton filling leads to an increase in the heat loss coefficient a_{60}[2] of 0.11 W/(m²K) whereas

---

[2] The heat loss coefficient a_{60} represents the heat losses at a temperature difference between fluid and ambient air of 60 K. It can be calculated as follows: $a_{60} = a_1 + 60\ \text{K} \cdot a_2$.

the air filling leads to a decrease of 0.18 W/(m²K). However, the material costs for krypton are 100 times as high as for argon and its availability is limited. Thus, an argon filling seems to be more advantageous for practical implementation.

3. Reliability of the collector

The significantly reduced heat losses through the insulated transparent cover lead to increased stagnation temperatures compared to a basic flat plate collector. Temperatures up to 264 °C were measured on the absorber-plate at standard conditions (G = 1000 W/m², T_{amb} = 30 °C). Standard single glazed collectors with antireflective coated glass can reach a maximum temperature of only 210 °C. The collector components have to withstand the increased temperature loads. Investigations with different solar absorbers, varying the materials (copper, aluminum) and the piping geometry (harp, serpentine), were performed, with focus on the thermo-mechanical loads and resulting deformation at high temperatures. For details on these investigations, we refer to Ref. [4]. In the present paper reliability tests on the hermetically sealed double-glazing, as a novel collector component, and on the overall collector are presented.

3.1. Double-Glazing

The low-e double-glazing is a new component for flat plate collectors. To test the reliability of this component for architectural application, standardized test methods are available [5,6]. As particularly the thermal loads of the glazing, when used in collector application, are significantly higher, new test methods are developed, to be able to test the temperature and UV-stability of the collector glazing.

In a first step, the maximum temperature loads at relevant collector components were determined. Therefore, temperature measurements with an unconnected collector during stagnation were performed in a sun-simulator. Figure 3 shows the measured temperatures at different positions at the glazing and the absorber plate of the collector. A maximum temperature of 264 °C was obtained on the absorber plate at 2/3 of the total length. The absorber plate exhibits a distinctive temperature profile in longitudinal direction. At the bottom of the absorber a temperature of only 158 °C was measured.

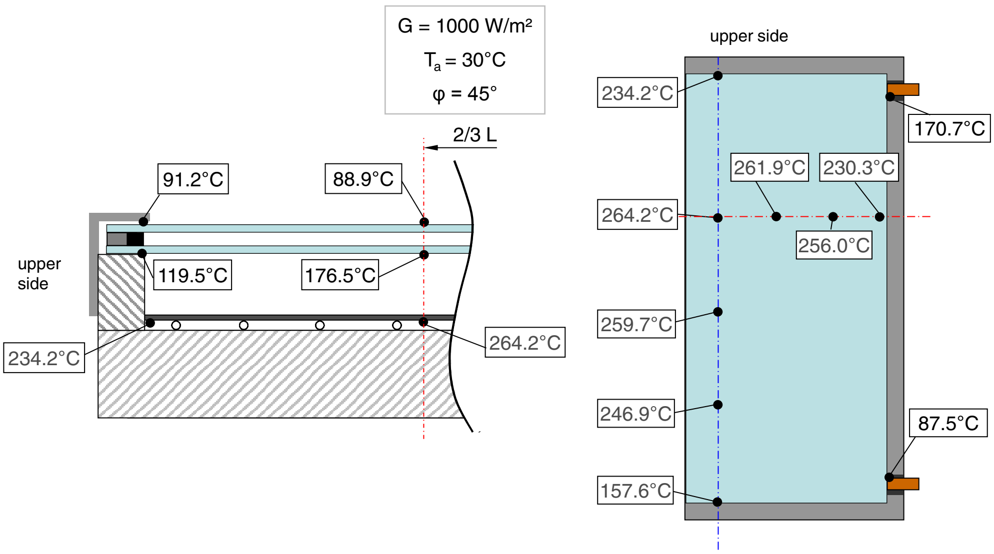

Fig. 3. Measured stagnation temperatures at the upper part of the collector (inclination angle 45°) in a longitudinal section (left drawing) and on the absorber-plate in top view (right drawing) under standard conditions (G = 1000 W/m², T_a = 30°C).

The temperature stability of the hermetically sealed double-glazing was tested in a test rig developed at ISFH (see Figure 4), which emulates a temperature distribution in the glazing, that corresponds to the application in a collector in case of stagnation. When the sealed double-glazing is heated up, the pressure of the inner gas-filling is increased, which induces thermo-mechanical loads in addition to the temperature loads in the glass panes and particularly in the sealing materials of the edge bond. The inner pressure and the deformation of the glass panes strongly depend on the size and the thickness of the glass panes and the gap width between them [1,7]. Thus, it is necessary to use a glazing specimen in collector size to reproduce realistic loads. During the load test, two glazing samples (1850 mm x 1230 mm) were tested at a maximum temperature of 140 °C in the edge bond, which is due to an increased safety factor 20 °C higher than the expected maximum temperature in the edge bond (see Figure 4). The temperature load is performed cyclically, with six hours exposure at stagnation temperature and two hours in which the edge bond is cooled down to 60 °C and heated up again to 140 °C. This induces an alternate load, qualitatively reproducing the natural day/night cycle in a collector.

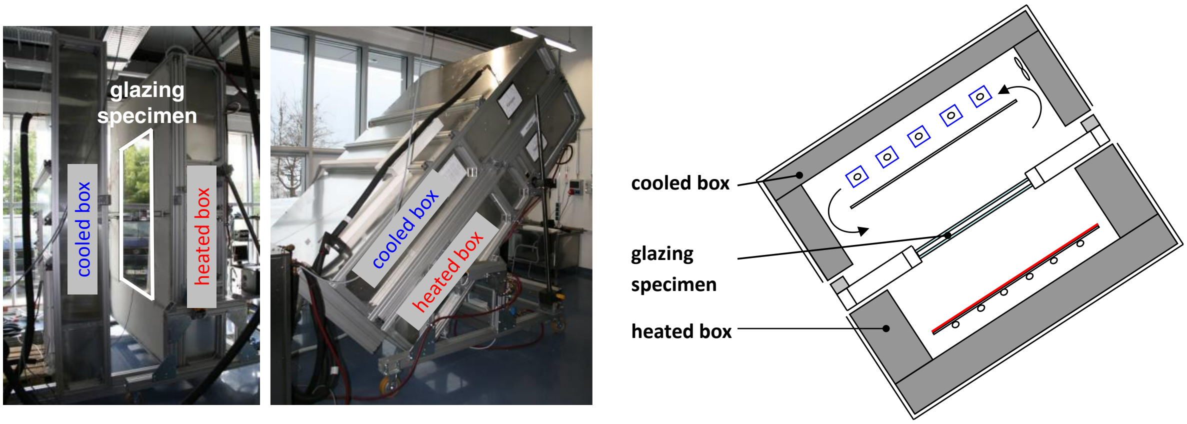

Fig. 4. Test rig for the high temperature stability tests of sealed double-glazing in collector size.

The test is performed with a load duration of 1200 h at stagnation temperature. To assess the applied load profile, system simulations with TRNSYS [8] with a solar heating system in a single-family house (140 m² living area) equipped with a collector area of 30 m² (45° inclination, south-facing orientation) and a storage tank with a volume of 2 m³ are carried out. For details of the standardized system simulation, which was developed in Task 32 of the Solar Heating and Cooling Programme of the International Energy Agency (see Ref. [9]). The frequency distribution of the temperature at the edge bond for one year of operation is simulated for South European (Barcelona, ES) and Central European (Braunschweig, GER) weather using the Meteonorm weather database [10]. Based on the measured frequency distribution of the sealing temperature of the tested glazing samples throughout the whole test period and the simulated frequency distribution for one year of operation, an equivalent exposure time is calculated. The basis for this calculation is the assumption that per 10 K increase of the sealing material temperature, the thermal load on the material doubles. The equivalent load temperatures for the two tested samples are shown in Table 1.

Table 1. Calculated equivalent exposure times of the two glazing samples as a result of the high temperature load test.

	Test sample A	Test sample B
Equivalent exposure time in Southern Europe	28 years	30 years
Equivalent exposure time in Central Europe	75 years	80 years

To test the gas tightness of the sealing materials, the level of gas filling, that means the argon concentration in the glazing cavity, is measured during the load test. As Figure 5 shows, the argon concentration was reduced by less than 7 percentage points for each test sample. This very low reduction of the argon concentration results in a decrease of the annual collector yield of less than 1 %.

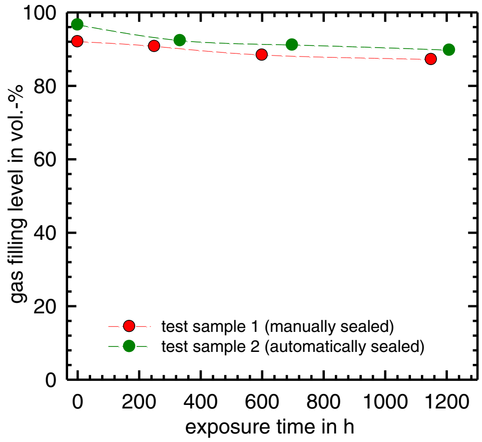

Fig. 5. Measured argon concentration of the two glazing specimens during the high temperature exposure test.

In another test, the stability against UV radiation in combination with high temperature and thermo-mechanical loads were investigated with two glazing specimens. To limit the costs and effort for such test rig, the size of the glazing specimens was scaled down to 700 mm x 500 mm. The test rig is equipped with 15 high pressure discharge lamps (Osram Ultra-Vitalux®), which produce an average irradiance in the UV-wavelength range ($\lambda = 280$ - 380nm) on the edge bond of the whole specimen of 80±10 W/m². Throughout the test time, it decreases to 60±10 W/m². Compared to natural irradiation with AM 1.5, which produces an UV-intensity of 52 W/m² at 1000 W/m² solar irradiance [11], the UV test is performed with a low acceleration. One sample was tested with an average temperature at the edge bond of 100±10 °C and the other one of 120±10 °C. The UV load test is performed in cycles, consisting of 11 h with irradiation and 1 h without irradiation. The test duration and the resulting equivalent exposure time, calculated using the same method described for the high temperature load test, is shown in Table 2.

Table 2. Test parameters and calculated equivalent exposure times of the two tested glazing samples for the combined UV- and temperature load test.

	Test sample UV1	Test sample UV2
Visual inspection	No irregularities	No irregularities
UV-intensity	80…60±10 W/m²	80…60±10 W/m²
Average edge bond temperature	100±10 °C	120±10 °C
Equivalent exposure time in Southern Europe	7 years	17 years
Equivalent exposure time in Central Europe	19 years	46 years

By performing a visual inspection after the exposure, no irregularities at the two glazing specimens were detected. Measurements of the gas filling level resulted in an absolute decrease of the argon concentration of 4 % (UV1) and 5.7 % (UV2), respectively (see Table 3). Even smaller effects are expected with collector size glazing. As mentioned before, this low reduction of the argon concentration affects the collector yield less than 1 %.

Table 3. Results of the visual inspection and the gas filling level measurement.

	Test sample UV1		Test sample UV2	
	Before test	After test	Before test	After test
Visual inspection	No irregularities	No irregularities	No irregularities	No irregularities
Argon concentration	96.5 %	92.5 %	98.0 %	92.3 %

3.2. Collector

To test the reliability of the overall collector, a one-year outdoor exposure test on the ISFH test roof was performed with four unfilled prototype collectors. Before and after the exposure, the collector efficiency curve was measured in the ISFH sun simulator and the gas filling level of the double-glazing was determined.

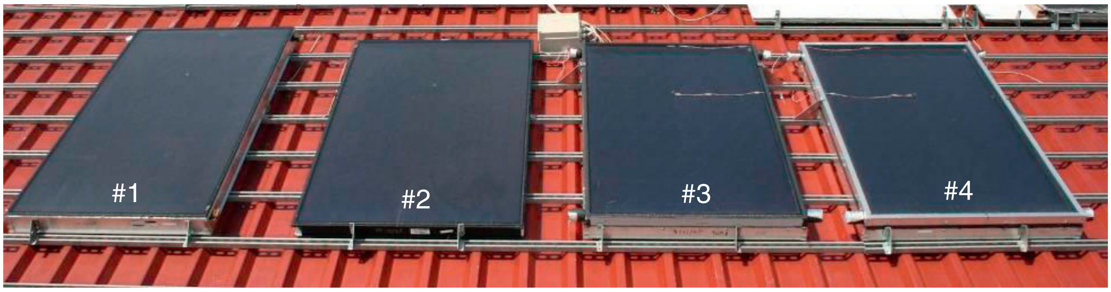

Fig. 6. Four prototype collectors on the ISFH test roof for a one year outdoor exposure test without fluid connection.

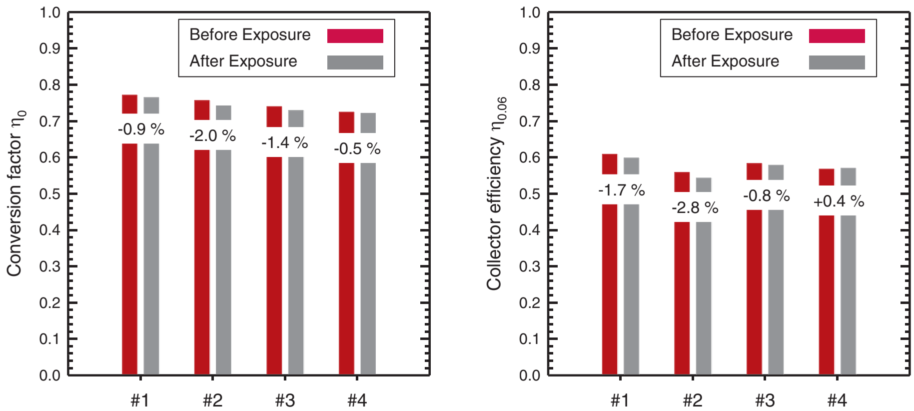

Fig. 7. Results of the collector efficiency measurements with the four tested collectors; left diagram: conversion factor η_0; right diagram: efficiency $\eta_{0.06}$ at a reduced temperature difference $\Delta T/G$ of 0.06 Km²/W; the numbers on the bars show the relative change in efficiency as percentage of the initial value before the exposure.

The results of the collector efficiency measurements are summarized in Figure 7. If the mean values of the four collectors are assessed, the conversion factor η_0 as well as the efficiency $\eta_{0.06}$ at a reduced temperature difference $\Delta T/G$ of 0.06 Km²/W are decreased by 1.2 % relatively. Compared to a published study with evacuated tube collectors (ETC) [12], these results are very promising: Throughout a one-year outdoor exposure in this study, the efficiency $\eta_{0.06}$ was reduced by 11.6 % (heat pipe ETC, mean value of 16 collectors) and 1.8 % (direct flow ETC, mean value of 3 collectors).

4. Economical estimation

To estimate the economic feasibility of the high efficiency flat plate collector, a simplified analysis was performed. The expected production costs of the new collector were calculated by the industry partners in the project. These costs were compared to the production costs of the standard products of collector manufacturers. As standard products, a single glazed flat-plate collector (FPC) with antireflective glass and an evacuated tube collector (ETC) were defined. The relative costs of the three types of collectors normalized to the costs of the FPC are shown in Table 4.

Table 4. Relative production costs (per aperture area) in relation to the production costs of the single glazed flat plate collector (FPC).

	Single glazed flat plate collector (FPC)	High efficiency flat plate collector (HFC)	Evacuated tube collector (ETC)
Relative production costs	1	1.5	2.45

Annual collector yield simulations at constant collector inlet temperatures throughout the year are carried out to assess the performance of the different types of collectors. Figure 8 shows the annual collector yields plotted against the collector inlet temperature. The results depend on the reference area: If the collector yield refers to the aperture area, the yields of the ETC in comparison to the FPC and HFC are higher as if the gross area is used. The reason is, that the relation of gross area to aperture area for FPC and HFC is significantly lower (typically between 1.05 and 1.1) than for ETCs (between 1.2 and 1.35). Usually, the available installation area is limited, thus the relation to the gross area is more valuable.

If the simulated collector yields are referred to the determined production costs, the optimum inlet temperature range is found to be between 80 °C and 110 °C, where the HFC is economically advantageous if compared to the standard industry products FPC and ETC. At inlet temperatures below 80 °C the FPC with antireflective glass is economically more efficient, above 110 °C the ETC is.

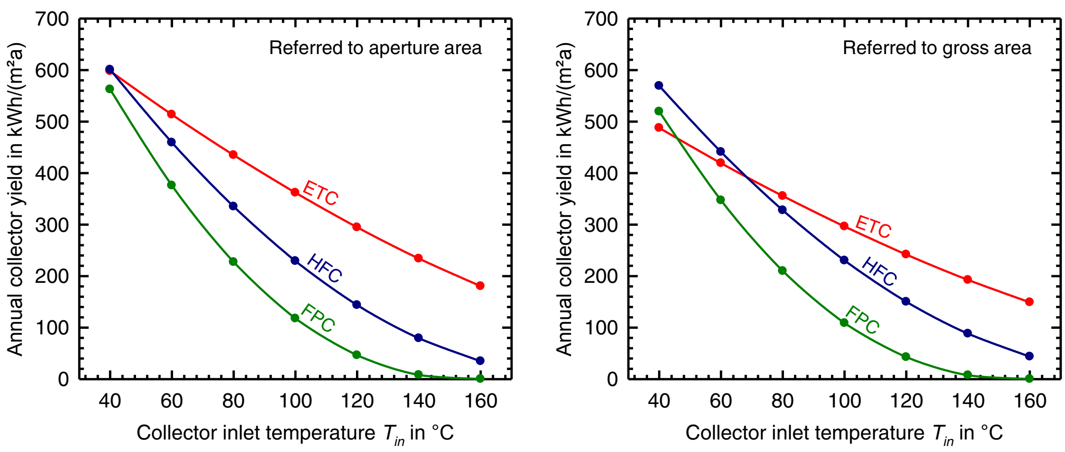

Fig. 8. Simulated annual collector yield with weather data of Zurich (Meteonorm [10]) for the three types of collectors; left diagram: collector yield referred to the aperture area of the collector; right diagram: collector yield referred to the gross area of the collector.

Another system simulation in TRNSYS concerning the coverage of the heat demand of a single family house with a high solar fraction based on the IEA Solar Heating and Cooling Programme (Task 32) [9] presented in chapter 3.2 was carried out with the three types of collectors with variable collector areas and weather data of Zurich [10]. To compare the performance of the three collectors, the fractional energy saving is used. This is a measure of the percentage the primary energy demand can be reduced with the solar system compared to a reference system without solar collectors. To define an economical advantageous collector dimensioning for the three collector types, the costs for the installed collector array is used, which includes the production costs of the collector and the costs for the assembly, the supports and the piping. According to [13] these costs are 40 % higher than the production costs of a single-glazed flat plate collector. Based on these costs and the simulated fractional energy savings, the collector types are economically assessed: The HFC has an economic advantage compared to the flat plate collector, if its higher costs per m² aperture area can be compensated by a smaller area requirement, which results in lower overall costs of the collector field. Similarly, a comparison between ETC and HFC is performed. As Figure 9 shows, an economic advantage for the HFC if compared with the FPC at a solar fraction above 48 % is calculated. The collector area of the HFC can be reduced by 26 % or more compared to the FPC. Compared to the ETC, the HFC is advantageous for all the collector areas studied.

It is noted that the economic considerations shown are very simplified as they are based solely on the costs of the collector field, the costs of the complete solar heating system are not considered.

Other important aspects that provide advantages of the new collector compared to the commercially available collectors are discussed in the following chapter.

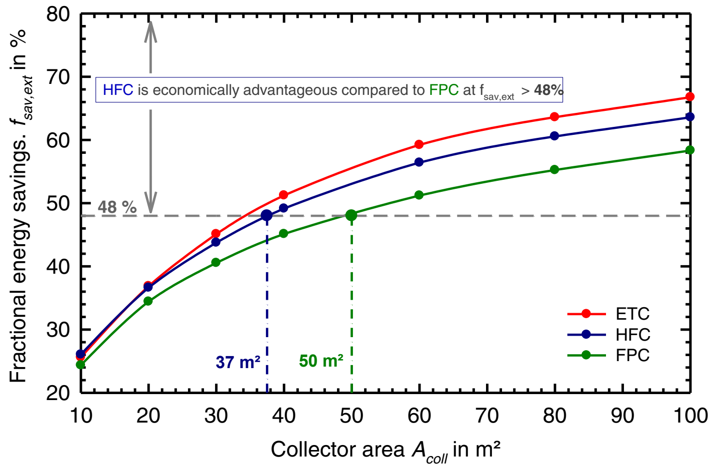

Fig. 9. Simulated fractional energy savings $f_{sav,ext}$ of the three collector types as a function of the collector area (aperture); weather data of Zurich (Meteonorm [10]).

5. Conclusion

As the key component of the underlying collector concept, high-transmittive low-e coatings based on transparent conductive oxides (TCO) were developed and transferred to industrial production. These glass panes were integrated into a hermetically sealed double-glazing with an argon-filling, which is used as a transparent cover of a flat plate collector. Performance measurements on an optimized prototype collector showed an increase in efficiency of 70 % compared to a standard single-glazed flat plate collector (ΔT = 60 K, G = 500 W/m²). The collector represents a new application for gas-filled double-glazing, which is usually used as window glazing in the building sector. As the standard reliability test procedures are only available for windows, new procedures were developed to test the reliability of the collector glazing against high temperatures and UV radiation. These tests were performed with different prototype glazing samples and confirmed their long term stability. By performing a one year outdoor exposure test with four prototype collectors, the reliability of the whole collector was tested successfully. A decrease in efficiency of only 1.2 % was reported as a consequence of the exposure.

By performing an economical estimation, an optimum operating range for the collector at temperatures between 80°C and 110°C was detected. In a solar heating system, the collector is economically advantageous compared to standard ETCs, independent of the collector array dimension.

This collector provides additional advantages compared to the conventionally used ETCs:

- As typical for flat plate collectors, a higher resistance against hailstorms can be expected.
- Since no vacuum insulation is applied, a sudden performance loss due to a leakage is avoided.
- The draining behavior of the typical flat-plate collector hydraulic is better (compared to a direct flow ETC), so the stagnation induced loads on the solar system are reduced.
- The flat plate collector design can be integrated into the building envelope more easily.

The HFC was developed up to a prototype status which can be transferred to industrial production. To generate a marketable product, it is now important to gain sustainable technological security with this new collector. Suitable applications like space heating systems with a high solar fraction and solar heating systems for industrial processes have to be implemented, supervised and evaluated scientifically.

Acknowledgements

The project HFK Low-e (FKZ 0325973 A-D) was funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) based on a decision of the German Federal Parliament. Project partners of the ISFH are Euroglas GmbH, Vaillant GmbH and Solvis Energiesysteme GmbH. Further the companies Kömmerling Chemische Fabrik GmbH and Bystronic-Lenhardt GmbH supported the project. The authors alone are responsible for the content of this publication. They are grateful for the support.

References

[1] Föste S. Flachkollektor mit selektiv beschichteter Zweischeibenverglasung (in German). PhD Thesis, Leibniz University Hanover, April 2013.
[2] Föste S, Giovannetti F. Thermal Insulation for High Efficiency Flat Plate Collectors, Proc. Eurosun 2012, No. 30, Rijeka, Croatia, September 2012.
[3] EN 12975-2:2006. Thermal solar systems and components – Solar collectors – Part 2: Test methods. Beuth Verlag, Berlin, 2006.
[4] Föste S; Müller S, Giovannetti F, Rockendorf G. Temperaturbedingte Verformung von Absorbern in hocheffizienten Flachkollektoren (in German). Tagungsband 23. Symposium Thermische Solarenergie, Bad Staffelstein, May 2013.
[5] Elmahdy H. Accelerated Aging of IG units: North American test methods. IEA Solar Heating and Cooling Programme, Task 27 workshop papers, 2009. www.iea-shc.org/publications.
[6] DIN EN 1279-2:2002, Glas im Bauwesen - Mehrscheiben-Isolierglas - Teil 2: Langzeitprüfverfahren und Anforderungen bezüglich Feuchtigkeitsaufnahme (in German). Beuth Verlag, Berlin, 2002.
[7] Föste S, John S, Rockendorf G. Verfahren zur Berechnung der temperaturbedingten mechanischen Belastung von Isolierverglasungen in Flachkollektoren (in German) Tagungsband 19. Symposium Thermische Solarenergie, Bad Staffelstein, Germany, 74-79, 2009
[8] Transsolar Energietechnik GmbH: TRNSYS Version 16.1. 2008.
[9] Heimrath R, Haller M. Project Report A2 of Subtask A: The Reference Heating System, the Template Solar System. Task 32, Solar Heating and Cooling Programme. International Energy Agency, 2007.
[10] Meteotest: Meteonorm Handbook, Parts I, II and III. Bern, www.meteotest.ch, 2003.
[11] American Society for Testing and Materials: Standard Tables for Reference Solar Spectral Irradiances: Direct Normal and Hemispherical on 37° Tilted Surface. AMTS-G-173, 2003.
[12] Khebchache B, Buscarlet C. One year exposure tests performed throughout Europe on different solar thermal collectors. Intelligent Energy Europe Project, IEE/08/593/SI2.529236, Deliverable D2.2 – R2.11, 2012. http://www.estif.org/fileadmin/estif/content/projects/QAiST/QAiST_results/QAIST%20D2.2_R2.11%20One_year_exposure_test.pdf
[13] Peuser FA, Croy R, Mies M, Rehrmann U, Wirth HP. Abschlussbericht zum Projekt 032 9601 L, Solarthermie2000, Teilprogramm 2, und Solarthermie2000plus wissenschaftlich-technische Programmbegleitung und Messprogramm Teil I. (in German) Projektabschlussbericht BMU, FKZ 0329601 L, Hilden, March 2008.