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Development of an insulated glass solar thermal collector

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Abstract

Insulated glass solar thermal collectors result from the insertion of a solar absorber into the outer gap of a multiple glazed unit. Taking advantages from the manufacturing technology of the glass and window industry, a flexible and highly automated production as well as an easier and architecturally more appealing integration into the building envelope is expected. Ensuring long-term functionality, on the other hand, represents a very challenging development task due to high temperatures and to the thermally induced deformations of the solar absorber. The paper analyzes the behavior of this new kind of collector by means of theoretical calculations and experiments, focusing on both the performance and the reliability aspects. Efficiency measurements according to EN 12975 on prototypes with a slim design report specific values comparable to those of standard flat plate collectors (η_0 = 0.78, a_1 = 3.77 W/m²K, a_2 = 0.011 W/m²K² for a 50 mm thick, argon-filled prototype). Prolonged exposure to stagnation temperature and internal thermal shock-tests attest the durability of collector configurations featuring temperature-resistant components and suitable constructions, able to reduce and compensate the absorber deformation.

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Keywords: insulated glass; flat plate collector; building integration

1. Introduction

A successful dissemination of solar thermal systems for hot water production and space heating requires not only the development of performing and cost efficient components, but also an improved integration into the envelope and system engineering of the building. An optimized building integration leads to a reduction of the installation costs, to a safer and low-maintenance operation and to a higher architectural quality.

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Among façade-integrated collectors new assemblies based on the manufacturing technology of the glass industry have been developed and investigated for this reason in recent times [1 - 5].

Insulated glass exhibits basic properties that can be advantageously used for the building integration of solar thermal collectors:

- The elements can be manufactured object-related, in almost any size and shape. This requires not only a corresponding variability in the production facilities, but also a matched logistics in the manufacturing processes.
- Despite the individuality of each element, insulated glass can be manufactured at low cost thanks to a high degree of automation, a simple basic construction and well-structured production processes.
- The elements are mounted in conventional window frames or façade profiles, thus simplifying the installation on-site (s. Figure 1). The assembly of frame and window systems itself is also a proven building standard.

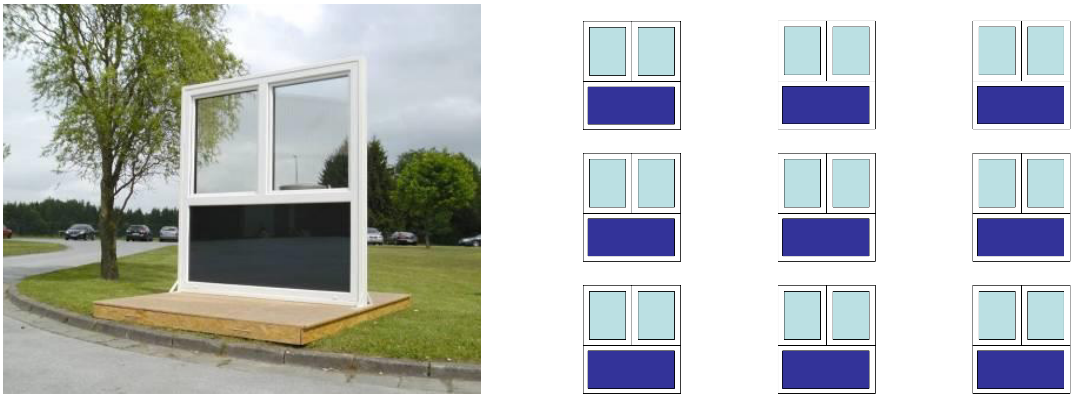

Fig. 1. Window frame system with insulated glass collector (left, source: Energy-Glas) and example of façade integration (right)

The use of gas-filled gaps and low emissivity (low-e) coatings on glass enables an effective reduction of the heat losses in combination with a slim design. Hidden behind promising approaches, many engineering challenges stand in the way of an introduction to the market so far. Crucial aspects are the integration of the solar absorber into the glazing unit and the long-term reliability of the collector under the usual thermo-mechanical loads occurring in operation and in case of stagnation. High temperatures and corresponding deformations of the absorber plate can affect the stability of the materials and of the overall construction and, in case of gaps filled with noble gases, the gas- tightness of the collector. For collector panels replacing an entire wall structure and thus constituting a room-enclosing surface, additional restrictions with regards to thermal comfort have to be taken into consideration.

Within the frame of a running project we are investigating the behavior of this new kind of solar thermal collector by means of calculations and experiments. We analyze different absorber constructions as well as different integration approaches, aiming at the development of a solution, which can provide for a high architectural quality and for the required durability.

The paper presents and discusses the basic aspects of the development, focusing on the results achieved in our investigations.

Nomenclature

a_1	linear heat loss coefficient according to EN 12975-2 in W/(m²K)
a_2	quadratic heat loss coefficient according to EN 12975-2 in W/(m²K²)
a_{40}	effective heat loss coefficient at $\Delta T = 40$ K in W/(m²K)
G	hemispherical irradiance in W/m²
h_c	convective heat transfer coefficient in W/(m²K)

h_r	radiative heat transfer coefficient in W/(m²K)
T_a	ambient air temperature in °C
T_{fl}	mean fluid temperature in K
T_{in}	internal air temperature in °C
α	solar absorption
β	collector tilt angle in degree
ε	thermal emissivity
η	collector efficiency
η_0	conversion factor according to EN 12975-2
τ	solar transmittance

2. Collector design and heat transfer mechanisms

An insulated glass solar thermal collector results from the combination of an insulating multiple glazing and a flat plate collector. In order to minimize the optical losses the solar absorber is positioned between the first (outer) and the second glass pane, even if the use of a double glazing as cover is also feasible with the aim of increasing the collector insulation and its efficiency, following an approach investigated in current research activities [6; 7]. The type of cover (iron content and optional antireflective coatings) affects the conversion factor, which thus doesn't differ from that of a common flat plate collector. As solar absorber different assemblies can be taken into consideration: sheet-and-tube, as finned or full-surface construction, as well as direct flow one. More complex multifunctional design exhibit additional components like reflectors or light-redirecting elements in order to fulfill special requirements and provide for visual and/or thermal comfort [1; 2]. The choice of the absorber is responsible not only for the performance, but especially for the reliability of the collector. To this regard the fixings and the pipe connections play a major role, as described in Section 3.2.

The common backside insulation of a flat plate collector is replaced by one or more glass panes and corresponding gaps, acting as radiative shield and convection barrier. The number of panes and gaps, the gas filling (air or noble gases like argon and krypton, commonly in use in architecture) and the emissivity of the glass surfaces, which can be significantly reduced by the application of metal coatings, determine the heat losses of the collector. The present work focuses on the triple-glazed design, which represents a good compromise between performance, weight and costs. The resulting, simplified thermal resistance network, comparable to a large extent to that of an insulating glazing, is depicted in Figure 2.

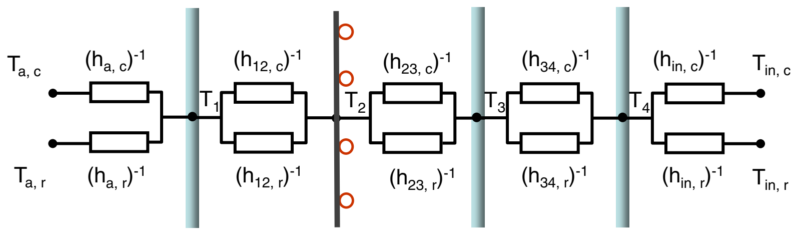

Fig. 2. Simplified, one-dimensional thermal resistance network of an insulating glass flat plate collector, referred to the undisturbed, "centre-of-glass" region of the panel

Figure 3 shows the effective heat loss coefficient at a temperature difference of 40 K between ambient air and heat carrier fluid for different triple-glazed configurations ($a_{40} = a_1 + a_2 * 40$ K in W/m²K). The calculation is carried out with a simulation tool developed at ISFH to reproduce steady and unsteady, one-dimensional heat transfer mechanisms in flat plate collectors on the basis of the geometrical, thermal and optical properties of the single components as well as on the operation conditions [6; 7]. The program has been modified and adapted in this case to the new glass collector design. The calculation refers to the undisturbed region of the collector (corresponds to the so-called "center-of-glass" of architectural glazing) and assumes plane-parallel panes with a homogeneous surface temperature distribution. The convective heat losses are estimated according to the empirical models usually implemented for rectangular gas cavity [8]. Thermal bridges (edge bond, connections and other fittings), higher convection heat losses due to temperature gradients over the glass and absorber surface or increased heat losses as a result of thermo-mechanical deformations of the collector components are not considered. These effects are known to significantly contribute to the overall insulation of flat plate collectors [7; 9]; a similar or even more pronounced impact is expected for the glass collector as well. The calculation serves to explain the function and influence of the different design parameters on the collector performance. Comparison between calculations and measurements are featured and analyzed in Section 3.1.

The optimum size of every single gap depends on the gas used, the collector tilt angle and the temperature of the corresponding enclosure surfaces. According to the theoretical models 6 (krypton) to 10 mm (air) and 8 (krypton) to 14 mm (air) are the best choice for the outer and middle gap, for 45° and 90° inclination respectively. The size of the inner gap doesn't affect the collector performance significantly. Based on practical experience at ISFH with thermo-mechanical deformations of solar absorbers, a gap of 12 mm is chosen for all the gaps to carry out the exemplary calculation. Lower distances can indeed lead to a collision between glass panes and absorber and, thus, damage the collector components and even compromise the collector performance.

As boundary conditions an irradiance G of 800 W/m², ambient and internal air temperature of 25 °C and a wind velocity of 3 m/s are assumed.

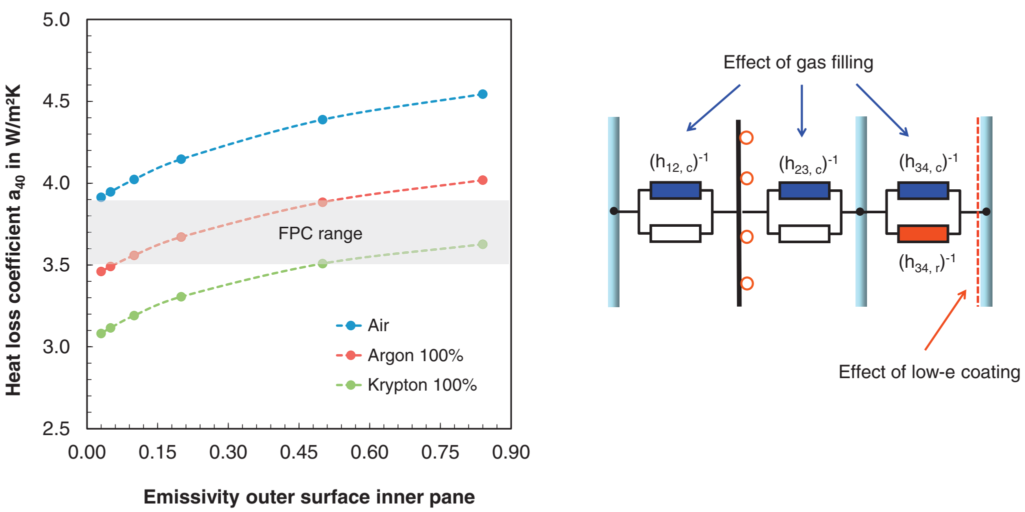

Fig. 3. Calculated "center-of-glass" heat loss coefficient a_{40} in dependency of the gas filling and the emissivity of the outer surface of the inner pane for a triple-glazed collector design. The simulated heat loss range of typical flat plate collectors is displayed for comparison

The results displayed in Figure 3 attest the promising insulating property of the triple-glazed collector, equal or even better than that of a common flat plate design, depending on the glass surface emissivity and on the gas filling.

The use of a low-e coating to suppress radiative heat transfer can advantageously affect the performance of the collector if applied on the outer surface of the inner pane. We estimate a heat loss reduction up to 0.55 W/m²K by decreasing the emissivity ε from 0.84 (uncoated glass) to 0.03 (common architectural coated glass), which corresponds to an improvement of about 15 – 20%. An additional coating on the outer surface of the middle pane can marginally (0.1 W/m²K) reduce the heat losses and only in combination with a highly emissive absorber backside (anodized or aged metal plate).

Replacing the air-filling with noble gases can further increase the collector insulation between 0.7 W/m²K (argon) and 1.1 W/m²K (krypton), which corresponds to an improvement of about 20 – 25%. For the use of krypton the higher cost (0.35-0.40 €/l against 0.04 €/l for argon) and its low availability have to be taken into consideration.

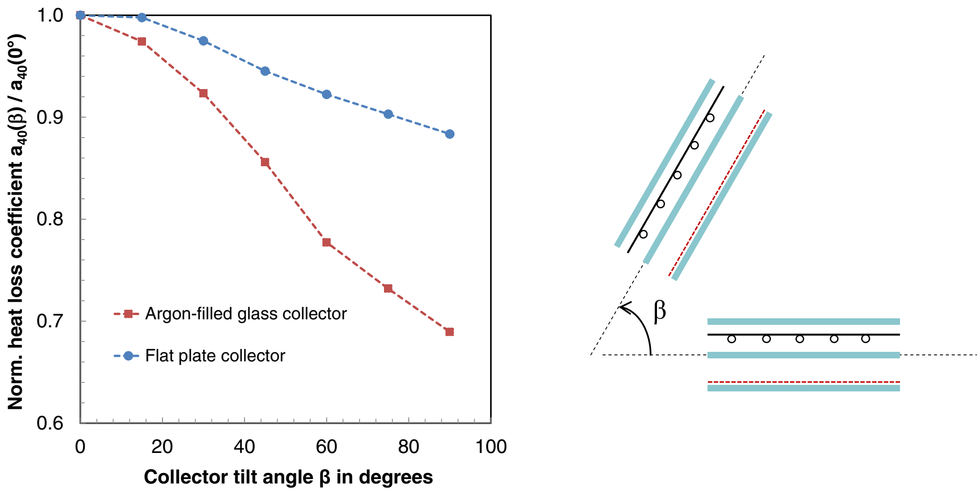

Fig. 4. Calculated normalized "center-of-glass" heat loss coefficient $a_{40}(\beta)/a_{40}(0°)$ in dependency of the tilt angle for an argon-filled, triple-glazed glass collector with a low-e inner pane compared to that of a common flat plate collector, as reported in [11]

Our calculation results attest the stronger influence of the tilt angle on the collector performance compared to an usual flat plate design, as shown in Figure 4, due to the multiple gaps and the corresponding increased effect of the convective heat transfer: between 45° and 90° inclination we report a reduction of the heat losses of 0.6 W/m²K, twice as high as that of a common flat plate collector, as documented in the literature [10; 11].

3. Measurements on collector prototypes

3.1. Collector performance

On the basis of previous works as well as of the calculation results featured in Section 2 our experimental investigations focus on the promising argon-filled triple-glazed design with a low-e coated inner pane. In order to fulfill the ambitious requirements with regards to performance, reliability and aesthetics we analyze different commercial available and custom-made selective solar absorbers.

The efficiency measurements are carried out according to EN 12975-2 [12] with our indoor sun simulator, which ensures a high reproducibility and an uncertainty of less than 0.01 over the relevant temperature range. To investigate the effect of the argon filling, both filled and unfilled prototypes with an overall thickness between 50 and 60 mm have been tested.

The efficiency curves of two collectors at different tilt angles are presented in Figure 5 and compared to those of a commercially available flat plate collector. Both prototypes exhibit a 4 mm thick, low-iron glass cover ($\tau = 0.90 \pm 0.01$) and a highly selective sheet-and-tube absorber ($\alpha = 0.94 \pm 0.01$, $\varepsilon = 0.05 \pm 0.02$). The reference collector features a low-iron glass cover ($\tau = 0.90 \pm 0.01$), a selective absorber, consisting of a 0.4 mm thick aluminum plate and copper pipes ($\alpha = 0.94 \pm 0.01$, $\varepsilon = 0.05 \pm 0.02$), and 50 mm backside insulation.

The results confirm the expectations and, thus, the competiveness of the new collector, whose performance equals or even exceeds that of the reference flat plate design. Our simplified theoretical calculation referred to the undisturbed "center-of-glass" underestimates in general the heat losses of about 15-20%, but can reproduce the effect of gas filling and tilt angle expressed as percentage with a good agreement. The comparison between simulations and experiments are summed up in Figure 6.

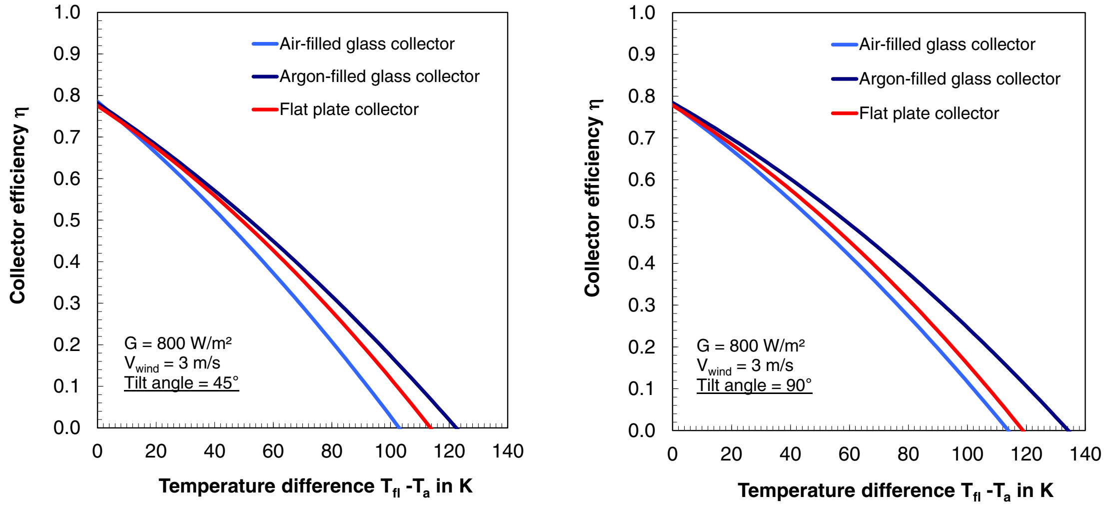

Fig. 5. Measured collector efficiency curves of air- and argon-filled triple-glazed prototypes, with an overall thickness of 60 and 50 mm respectively, at 45° (left) and 90° (right) tilt angle compared to those of a common flat plate collector

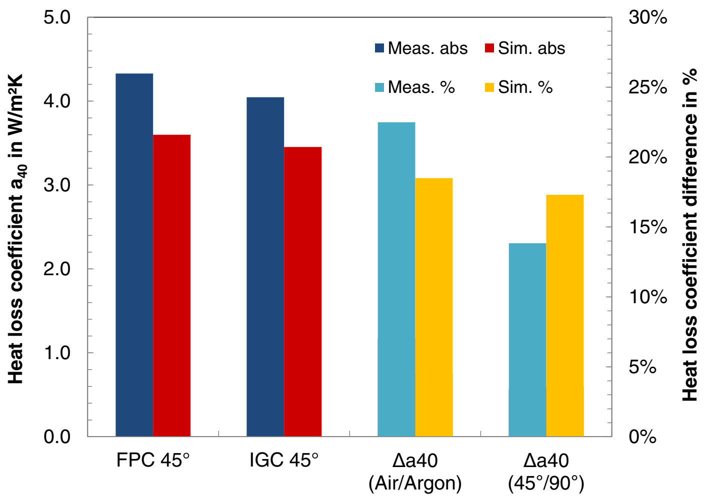

Fig. 6. Comparison of measured and simulated effective heat loss coefficients a_{40} of triple-glazed glass collectors and a common flat plate design

3.2. Reliability aspects

The performance results on insulating glass collectors reported in our work confirm the experience of previous investigations [3; 4]. Ensuring long-term functionality, however, represents the most challenging task in developing this new collector design and according to the authors is one of the main reasons which have prevented its successful introduction to the market so far.

Compared to architectural glazing, insulating glass collectors are exposed to much higher temperatures under operation and stagnation conditions. At the edge bond, a very sensitive component of the collector, responsible for the durability of the insulated unit (gas-tightness and moisture penetration), temperatures up to 130 °C were recorded, depending on the specific assembly and test conditions. Occurring glass surface temperatures above 100°C and temperature gradient above 40 °C require the use of toughened panes.

Due to the gas tightness of the glazing, the significant temperature changes inside the collector are responsible for continuous pressure increase or decrease in the gap and for corresponding deflections of the glass panes. Figure 7 shows the theoretical maximum deflection of a 1 x 2 m² large and 4 mm thick pane in an argon-filled double glazing at 90° tilt angle, as a function of the mean gap temperature and size. The model used was adapted from the literature [13] and validated at ISFH for solar thermal applications [14]. Experimentally measured displacements of the front and back glass up to 15 mm with an estimated mean temperature of 110-115° C confirm the strong impact on the assembly and show an unexpected good agreement between the simplified theoretical simulation and the experiments. For the calculation an effective gap size resulting from the sum of all the collector gaps is assumed. The presence of the suspended solar absorber as well as of the middle pane, provided with a borehole for compensating pressure differences, is neglected.

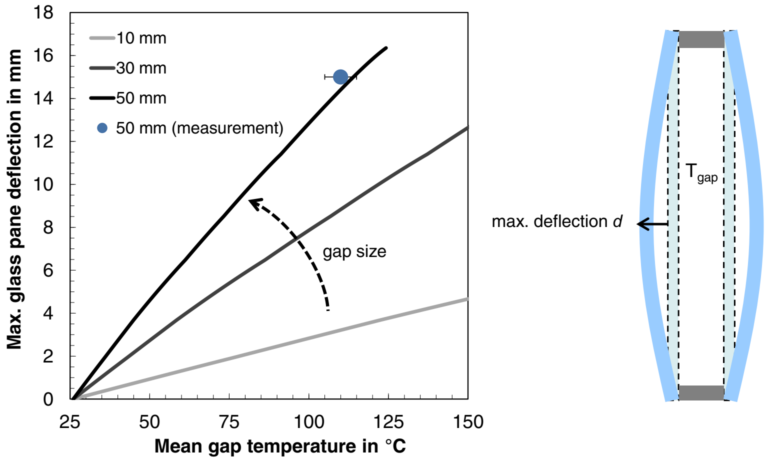

Fig. 7. Maximum deflection of a 1 x 2 m² large and 4 mm thick glass pane in an argon-filled double glazed unit at 90° tilt angle in dependency of the mean temperature of the gap: calculation according to [14] as well as single point indoor measurement on a triple-glazed collector prototype under stagnation conditions (G = 970 W/m², T_a = 30°C, no wind)

As a result, the edge bond is exposed to a severe thermal and thermo-mechanical stress, which cannot be withstood by conventional primary and secondary sealants for architectural glazing. For the specific application suitable thermoplastic materials from the German company Kömmerling Chemische Fabrik are implemented. These materials were developed for solar collectors and exhibit a higher mechanical strength as well as a superior thermal resistance. Their long-term stability has been proven up to 140 °C in a recent R&D project [6; 7].

Beside the glass pane deflections, the thermo-mechanical behavior of the solar absorber plays a crucial role with regard to the collector reliability. On the one hand, temperature induced deformations can determine collision with the glass panes and damage sensitive collector components. On the other hand, a not correctly designed collector can lead to increased thermal losses (thermal bridges and/or suboptimal gap sizes) and, thus, to a reduced performance. Additionally, mechanical stress on the pipe connections can affect the gas-tightness of the sealed collector. As the choice of materials, geometry and manufacturing technology can strongly influence these effects, we are evaluating different absorber assemblies. To reduce and compensate the absorber deformation without impairing the appearance of the front surface, custom-made fixings are applied on its backside.

The reliability of the collector prototypes is investigated by means of indoor and outdoor tests. Extended internal shock-tests similar to EN 12975-2 are carried out with our sun simulator: during these tests, the unfilled collector is exposed to high temperatures over three hours under stagnation conditions (irradiance G about 1000 W/m², ambient air temperature T_a about 30°C, no wind) and subsequently fast cooled down and flowed with cold water over one hour at a constant temperature of about 20 °C. The test procedure consists of 5 shock cycles. As assessment criteria, a visual inspection of the construction as well as a performance measurement and a measurement of the gas-tightness after exposure are carried out. During the test the collector temperatures (resistor sensors PT-100) and the gap size between absorber and cover glass at 9 positions (laser distance meter) are recorded, in order to analyze the behavior of the collector components and the effect of the fixings.

Our first results attest that the insulation property of the collector can be ensured only by using suitable materials and designs. For selected prototypes we report no increase of the heat loss coefficient a_{40} and no significant reduction of the argon concentration after the exposure, as shown in Figure 8.

The outdoor investigations are currently running. Two unfilled prototypes are exposed on one of our test roofs. Collector temperatures (absorber, glass panes and edge bond) as well as weather data (ambient temperature, wind speed and direction, hemispherical and diffuse irradiance) have been collected since August 2013. No visible degradation and no decrease of gas concentration have been reported so far.

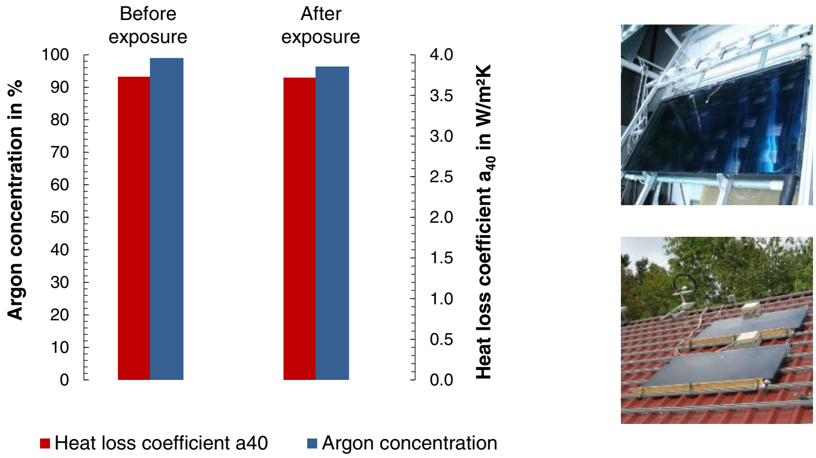

Fig. 8. Change in heat loss coefficient a_{40} and argon concentration of selected glass collector prototypes after shock-tests in our sun simulator (left) and exposure tests running at ISFH (right)

The exposure tests will be continued until September 2014 to prove the long-term stability of materials, components and of the overall construction.

4. Conclusion

Insulating glass solar thermal collectors combine the advantageous design and manufacturing technology of architectural glazing with the active use of solar energy and offer a promising solution for a flexible and object-oriented integration into the building envelope. Our work attests the performance of these collectors, which can achieve and even exceed the efficiency of commercially available flat plate collectors with a very compact design. Due to the temperature stress and the corresponding thermo-mechanical deformation of the components and the overall system, the reliability of the collector represents the most challenging development task. By using high-performance sealant materials with superior thermal and mechanical properties as well as suitable fixings for reducing and compensating the absorber displacement, the gas-tightness and, thus, its insulating property can be provided.

Ongoing activities are focusing on the further optimization of the design, aiming at simplifying the construction and adapting it to the manufacturing steps of the insulating glass production. The long-term reliability of the collector has still to be proven by means of extended indoor and outdoor investigations.

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