BASICS FOR THE DEVELOPMENT OF A HIGH EFFICIENCY FLAT-PLATE COLLECTOR WITH A SELECTIVELY COATED DOUBLE GLAZING

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1. Introduction

Many future applications of solar thermal energy, like heating with a high solar fraction and solar industrial process heat or solar cooling will require high collector efficiencies at temperatures above 80°C and/or at a low irradiance level. Advanced flat-plate collectors show a high potential for these applications, they are less expensive and mechanically simpler than evacuated tube collectors. To raise the performance of flat-plate collectors the thermal resistance of the transparent cover has to be increased, while keeping the solar transmittance at a high level. Within a research project[1] ISFH achieved this goal by adding a second glass pane with a low emitting coating and using argon in the hermetically sealed gap, thus reducing heat losses by both convection and radiation (see Fig. 1). A high solar transmittance must be realized by using high quality glass with antireflective coatings and an optimized low-e coating. Long term reliability of the coated glass as well as of the glazing system for the use in solar thermal collectors has to be assured. The objective of the project is to assess the technological and scientific basics for this collector concept. This paper gives an overview of the main project results.

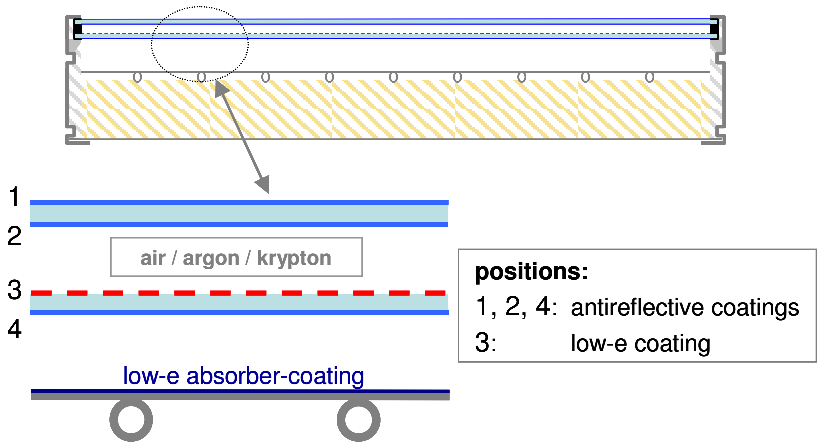

Fig. 1: Schematic collector concept, sectional view

2. Development of a low-e coating on glass

Since approximately 20 years low-e coatings are used in architectural double glazing systems to reduce the heat losses. Compared to architectural glazing the requirements for the coating properties of a collector glazing are completely different. An architectural glazing is optimized for a very low emissivity and a high light transmittance (visible wavelength range). For collector applications it is necessary to reach a high transmittance over the whole solar spectrum, the requirement for a low emissivity becomes less important if compared to windows, because the heat loss mechanisms are more complex. Furthermore it is essential to provide for a temperature resistance up to 160°C.

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To fulfill these requirements, we developed a three layer coating system with a functional low-e coating based on a TCO-material (transparent conductive oxide). As TCO material we have chosen aluminum doped zinc-oxide (ZnO:Al), because it has good optical and electronic properties, it is comparatively inexpensive and not toxic. The TCO functional layer is enclosed by two dielectric layers, each with adapted refractive index and layer thickness, which work as antireflective coatings. Further the upper layer works as a protective layer against oxygen and humidity. This coating system is currently produced on laboratory scaled glass surfaces of 10 x 10 cm² by reactive and non-reactive sputter technique. Using a glass substrate with a low iron content, a solar transmittance of 85% and a solar reflectance of 7% is achieved (Ehrmann and Reineke-Koch, 2011). By applying an additional antireflective coating on the opposite surface of the glass pane, the solar transmittance can be increased to 87.5%.

In Fig. 2 the transmittance and reflectance spectra of the developed coating system (ISFH) are compared with the commercially available TCO-based K Glass™ from Pilkington. K Glass™ was developed for architectural applications, thus it is optimized for a low emissivity, whereas the solar transmittance of 71% is to low for collector applications. Moreover the low solar transmittance is caused by a glass substrate with higher iron content and missing antireflective coatings.

The ISFH coating system shows a lower reflectance in the infrared spectral range if compared to K Glass™, which results in a significantly higher emissivity of 32% (K Glass™: 17%).

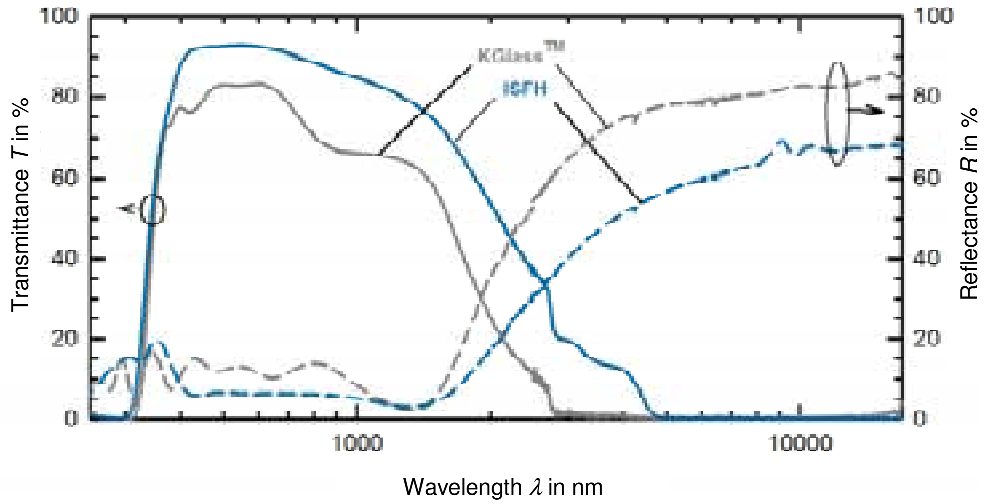

Fig. 2: Measured spectral transmittance and reflectance of the ISFH low-e coating system on a glass substrate with a low iron content, compared to the commercially available K Glass™

Another important requirement for the use of the low-e coating system in double-glazed solar collectors is the temperature stability due to the high temperatures of the low-e glass pane, which can reach up to 160°C in case of collector stagnation. Temperature load tests with coated glass specimens (540 h at 160°C) did not produce any change of the optical properties. Specimens of the new developed coated glass were additionally subjected to a condense water test for 540 h, which also did not show any change of the optical properties. According to these results the reliability of the coating may be expected, even if the edge bond of the glazing should be damaged and moisture would penetrate into the insulated glass unit.

3. Long term reliability of the glazing

The application of low-e coated double glazing in flat-plate collectors leads to significantly higher loads compared to windows. The increased temperature in operation and during stagnation is the crucial factor. Ageing effects and thermo-mechanical loads, resulting from the increase in pressure in the gas filled glazing, have to be considered in the design and material selection. Special high temperature resistant primary and secondary sealants were used to provide for the necessary durability of the glass unit. To investigate the long-term reliability of the glazing constructions, different tests in laboratory and on the ISFH test-roofs are carried out. Temperature, UV and humidity loads as well as thermo-mechanical loads are applied to different specimens and their impacts on the glazing properties are measured by different analysis techniques.

The temperature stability of double glazing in collector format is investigated in a self-developed test-rig. This test rig creates a temperature distribution in the glazing, which is to be expected in a stagnating collector. The load is applied cyclically with 6 h at stagnation temperature and 3 h for cooling down and heating up. The three specimens are tested each one at a different stagnation temperature in the edge bond of the glazing of 130°C, 140°C and 150°C for at least 400 h. These temperatures are partially higher than the expected maximum temperature of the edge bond in a stagnating collector of 135°C. By measuring the argon concentration of the gas filling and the thickness of the glazing as well as performing a visual inspection no degradation which affects the performance could be detected. According to our results the temperature resistance of the sealing materials in the edge bond of the glazing is expected.

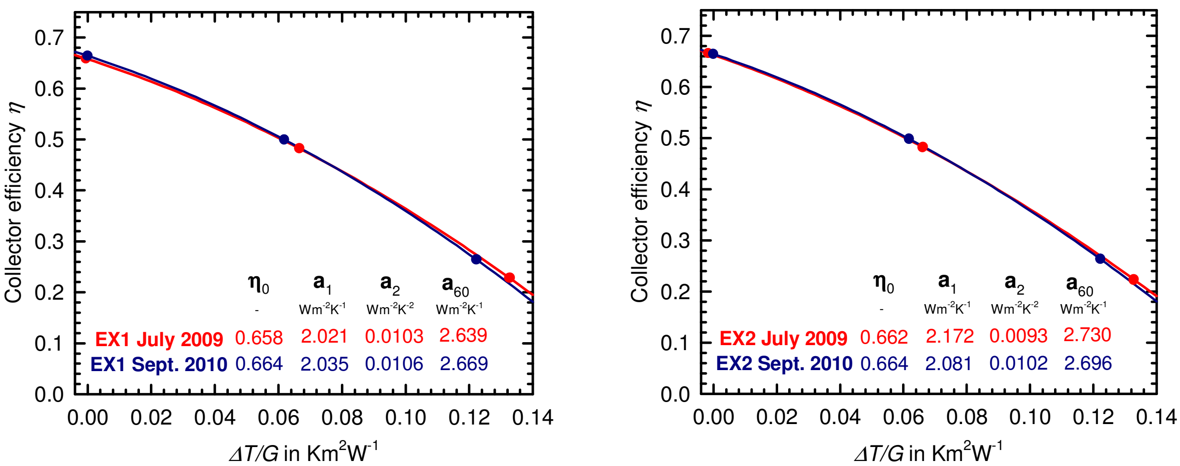

Fig. 2: Collector efficiency curves of a reference collector with a 50 mm back side insulation before the exposure (July 2009) and after 13 months of exposure (Sept. 2010) of two glazing specimens with K Glass™

Furthermore two glazing specimens are exposed to long-term natural weathering in stagnating collectors on the ISFH test-roof. The exposure started in July 2009. After 13 months of exposure the solar transmittance was measured as well as the thickness of the glazing and the dew point temperature in the glazing cavity (according to EN 1279-2) to detect moisture penetration. The results did not show any degradation, which could affect the performance of the glazing. This was confirmed by collector performance measurements with a reference collector. The two glazing specimens were applied to this collector, which was not exposed, to be able to measure solely ageing effects of the glazing. The collector efficiency curves before and after 13 months of exposition are shown in Fig. 3. The differences in the efficiency curves lie within the measurement uncertainty.

4. Collector performance

In addition to the optical properties of the low-e coated glass pane, the convective heat transfer in the two gas filled gaps of the collector affect the collector performance significantly. Experimental investigations concerning the optimum gap sizes and the influence of different gas fillings in the glazing cavity are presented in detail in Föste et al. (2010). According to these investigations best results are achieved with an air gap of approximately 25 mm between absorber and inner glass pane as well as with a hermetically sealed argon gap between the two glass panes. Krypton could further reduce the heat losses (about 2%), but it is much more expensive than argon.

As the developed high transmittive ISFH low-e coating system is up to now only produced in a laboratory scale, the expected collector efficiency parameters can not be obtained by measurements on a test-collector. Thus it is necessary to build a collector model, which allows predicting the performance of the new collector.

This stationary model consists of two parts, one optical and one thermal model. The optical model calculates the solar radiation transfer between the glass panes and the absorber plate including multiple reflections. It is possible to use spectrally resolved optical properties, as well as integrated values as input quantities. Outputs are the effectively absorbed fractions of the incident solar radiation in the absorber plate and in the glass panes. These are coupled into a thermal model, which calculates the one-dimensional heat transfer through the collector in normal direction to the collector plane. The model determines the heat transfer between the different temperature nodes of the collector by an iterative balance of the single heat fluxes. This heat flux balance method is based on a simplified model presented in (Duffie and Beckman, 2006). Further effects of thermal bridges in the collector frame and at the edge bond of the glazing are simulated with a finite-element-method and considered in the calculation. The model outputs are the temperatures of each node, the collector efficiency at different average fluid temperatures as well as the collector efficiency parameters (conversion factor η_0, heat loss coefficients a_1 and a_2). The model was validated by measurements with a test collector using K Glass™ as a low-e coated glass pane. The resulting efficiency curves with K Glass™ (measured and simulated) are shown in Fig. 4.

Further the expected efficiency curve of a double glazed flat plate collector with the ISFH low-e coating system on position 3 and additional antireflective coatings on position 1, 2 and 4 according to Fig. 1 is shown. The only difference between the ISFH collector and the K Glass™ collector is the reduced thickness of the back side insulation (mineral wool) of 80 mm (ISFH) instead of 100 mm (K Glass™). Due to the high solar transmittance of the ISFH coating system the conversion factor η_0 has significantly risen up to 0.78. However the heat loss coefficients are slightly higher compared to K Glass™. This is due to the decreased thickness of the backside insulation, the higher emissivity of the low-e coating system and the reduced absorption of the inner glass pane.

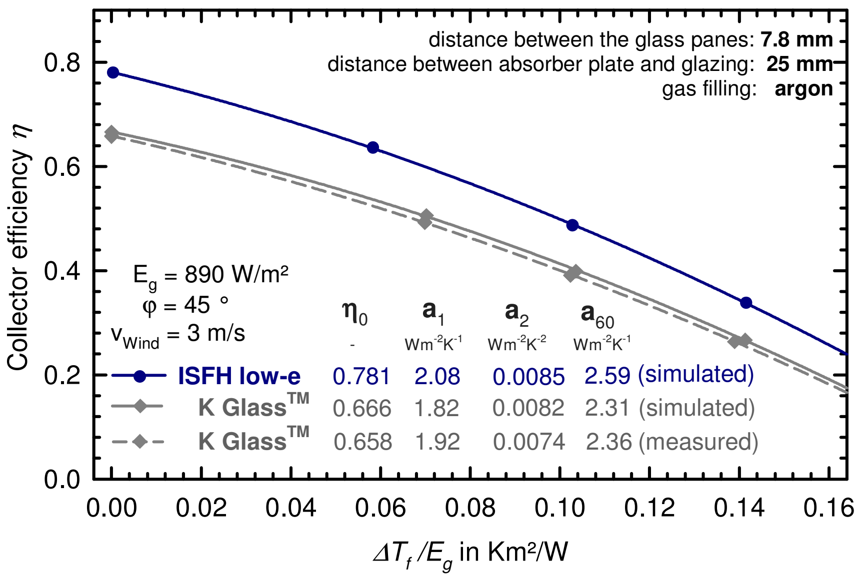

Fig. 4: Simulated collector efficiency curve with the ISFH low-e coating system on pos. 3 and three antireflective coatings (pos. 1, 2, 4) compared to a measured and a simulated efficiency curve of a collector with K Glass™ as a low-e coated glass pane

To carry out a simplified economic analysis for the high efficiency flat-plate collector (HFC), the expected production costs of the new collector are compared to those of the standard products single glazed flat-plate collector (FPC) and vacuum tube collector (VTC). This cost calculation was carried out by the three collector manufacturing project partners with support of the project partners Kömmerling and Bystronic.

Using simulations of the annual collector yield for the location Zurich at different constant inlet temperatures throughout the year, the performance of the three mentioned collector types is assessed. The results are shown in Fig. 5. For VTC and FPC the mean values of the standard products from the three collector manufacturing partners are presented. If the simulated collector yields are referred to the determined production costs, the optimum inlet temperature range is found to be between 70°C and 110°C, where the HFC is economically advantageous if compared to the standard industry products FPC and VTC. At inlet temperatures below 70°C the FPC is economically more efficient, above 110°C the VTC.

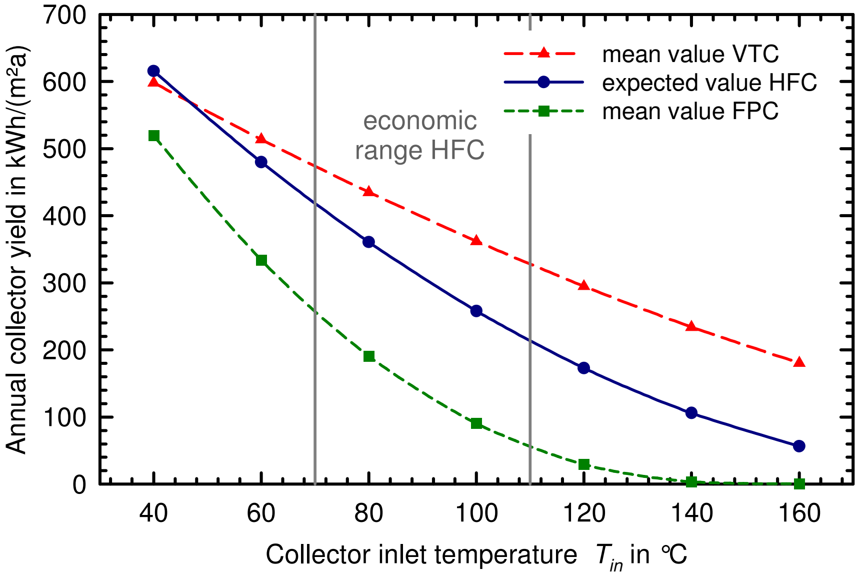

Fig. 4: Expected annual collector yield of the HFC compared to the VTC and FPC (mean values using the standard collectors of the project partners), Location Zurich (Switzerland), orientation south, inclination 45°, reference area aperture

Another comparative TRNSYS simulation concerning the coverage of the heat demand of a single family house with a high solar fraction based on the system from IEA SHC Task 32 (Heimrath and Haller, 2007) leads to an economic advantage for the HFC if compared with the FPC at a solar fraction above 37%. In this solar heating system the collector area of the HFC can be reduced by approximately 30% compared with the FPC.

5. Summary

The work presents the results of a research project aiming at the development of a high efficiency flat-plate collector with a selectively coated double glazing. A suitable low-e coating system based on a TCO-material for the new collector concept has been produced in laboratory scale. This coating system meets the requirements for the optical properties and shows a sufficient stability for the application in a flat-plate collector. Up to now we can expect the long term reliability of an insulating glazing working as a transparent cover in a flat-plate collector. The distances between the two glass panes as well as between the absorber-plate and the glazing have been optimized by experimental investigations, to minimize the convective heat losses. A collector model was developed and validated and could therefore be used to determine the expected efficiency parameters of the new collector equipped with the ISFH-low-e coating. The new collector is characterised by a conversion factor η_0 of 0.78 and a heat loss coefficient a_{60} of 2.59 W/(m²K) (temperature difference between fluid and ambient air ΔT = 60 K). On the basis of annual collector yield simulations for the HFC an economical operating range between 70°C and 110°C (inlet temperature) is identified, where the collector is economically advantageous compared to the established collector types single glazed flat-plate collector and vacuum tube collector. The transfer of this collector concept into a marketable product is subject of a currently running project, which is carried out at ISFH in cooperation with industry partners. Aim of the work is the development of industrially produced large scale glazing systems as well as prototype collectors.

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