Thermal Load Analysis of a Solar-Thermal Flat-Plate Collector in a Domestic Heating System

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Abstract

Considering the significantly increased costs for aluminium and copper that are at present primarily used in the solar-thermal flat-plate collector design, polymeric materials show a remarkable potential for cost reduction. Apart from moderate material costs especially for commodity plastics, highly efficient production processes provide an interesting prospective for the use of polymeric materials. However, several technological challenges have to be met prior to the use of polymeric materials in a wide range of applications for collectors. This is especially the limited thermal property of various polymers in comparison to copper, aluminium or glass.

Focussing on the evaluation of the thermal loads on the components of a flat-plate collector, an experimental analysis in combination with a simulation study of a modern state-of-the-art collector is carried out considering the following aspects: maximum temperatures of the collector components, dynamic behaviour of thermal loads and accumulated exposition times, i.e. thermal load profiles. Both the in-situ field-testing and the calculations show high thermal loads for the absorber and moderate temperatures for the other collector parts.

1. Background

All manufactures of solar-thermal systems aim at cost reduction especially regarding the collector. However, significantly increased market prices for aluminium and copper continuously obstruct these efforts. Against this background, the use of low-cost polymers in solar-thermal collectors shows several advantages. Besides the savings of costly metals, polymeric parts show remarkable properties in terms of handling and roof installation. Using modern manufacturing technologies for polymeric components promises production automation of collectors and hence considerable cost reduction potentials. Nevertheless, there are several technological challenges regarding the use of polymeric materials in solar-thermal collectors. The high thermal load on various parts of a collector seems to be the main hurdle next to the limited mechanical and UV-durability. Furthermore, the thermal conductivity of polymers is much lower compared to metals, especially copper.

In order to provide a basis for further collector and system developments, the *Centre of Excellence for Renewable Energy Research* of *Ingolstadt University of Applied Sciences* investigates the temperature loads of collector parts in a state-of-the-art solar thermal system for hot water supply and space heating in a field-test building. In addition to the measurements, a detailed numerical simulation model will be validated with the experimental data [1].

The project is funded by the *German Federal Ministry for Environment, Nature Conservation and Nuclear Safety* and the work is carried out within the framework of IEA-Task 39 „Polymeric Materials for Solar Thermal Applications“.

2. In-Situ Analysis of a Domestic Solar Heating System

A conventional solar system is analysed in a field-test building. The building is a one-family house inhabited by four persons. It is equipped with a modern 20 m^2 solar hot water and space heating system with customary flat-plate collectors. The measurement data are analysed regarding the following aspects: maximum temperatures at the collector components, dynamic behaviour of thermal loads and accumulated exposition times, i.e. thermal load profiles. The latter are a fundamental basis for polymeric material selection or development, for an evaluation of material property changes over the life time as well as for an adoption of solar-thermal systems and collector designs to polymer needs.

2.1. Measurement Equipment

Measurement equipment was applied to both the system and one collector in order to specify the thermal and pressure loads on the collector at casing, absorber, glazing and insulation in a state-of-the-art system in detail. Furthermore, a dry collector without connection to the solar-thermal system and fluid was installed to refer to maximum loads during continuous stagnation. Table 1 shows the parameters of the investigated collectors.

Table 1. Parameters of the Investigated State-of-the-Art Collector.

Parameter	Symbol	Value	Unit
Optical Efficiency	η_0	0.798	-
Linear Heat Loss Coefficient	a_1	3.34	W/(m^{2}K)
Quadratic Heat Loss Coefficient	a_2	0.0075	W/(m^{2}K^2)
Heat Capacity of the Collector	C	9.5	kJ/K

Figure 1 shows a part of the tested collector array and the temperature sensors applied at the frame of the collector.

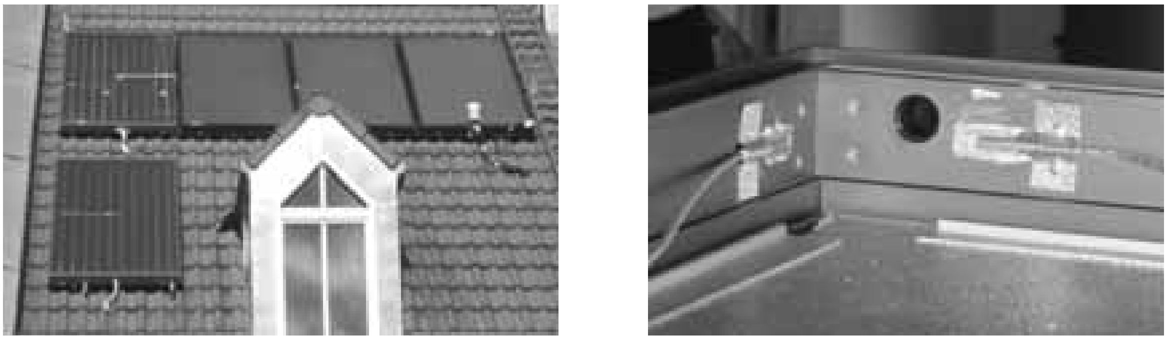

Fig. 1. Field-Testing of Collectors (left) and Exemplary Temperature Measurement Equipment at a Collector Casing (right)

2.2. Annual Field-Testing Results

In the following, measurement results are analysed in histograms with a class width of 10 K, considering data of one year (Jan. 2009 to Dec.2009), as for example shown in Figure 2. In order to provide a more detailed overview on durations at high temperatures, the vertical axis is limited to

500 h in the graphs, so that the comparably long durations at low temperatures, e.g. during night, are not shown. Furthermore, it has to be considered, that technical problems with the data acquisition led to 30 missing measurement days in March and June of the considered year.

The absorber in the system reached temperatures up to 140 °C while operation. In stagnating state, the absorber fin had temperatures up to 192 °C. These high temperatures were measured at the upper part of the collector near the outlet. Figure 2 shows the annual evaluation of this sensor. Despite the relatively large collector area, the solar-thermal system rarely was in stagnation, as the radiators in the basement of the heating system were used to avoid stagnation by cooling the buffer storage. The durations not displayed near the ambient temperature are 1,850 h for 0 °C, 1,940 h for 10°C and 988 h for 20 °C.

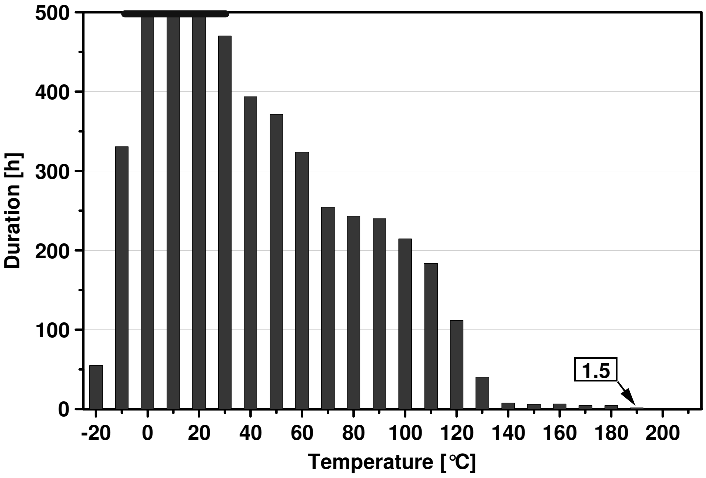

Fig. 2. Temperature Histogram of the Absorber Fin (collector in the system).

The hottest sensor of the dry absorber was in the central position of the part, where a maximum temperature of 208 °C was recorded. Figure 3 shows that the absorber reaches extreme temperatures frequently and quickly. During the measurement period shown, the absorber stayed over 1,100 h above a temperature level of 95 °C.

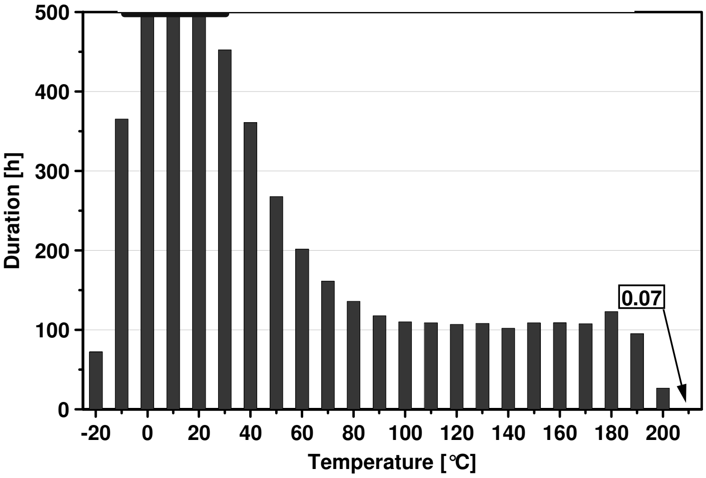

Fig. 3. Temperature Histogram of the Absorber Fin (dry collector).

The temperature of the cover sheet was measured with a shaded, bonded sensor at the inner surface in central position for both collectors. At the glazing of the collector in the system, temperatures above 55 °C mainly occurred during the stagnation state of the system (Figure 4). The maximum temperature was 82 °C. However, the temperature load is on a level that is considered to be uncritical for a wide variety of potential transparent cover sheet materials.

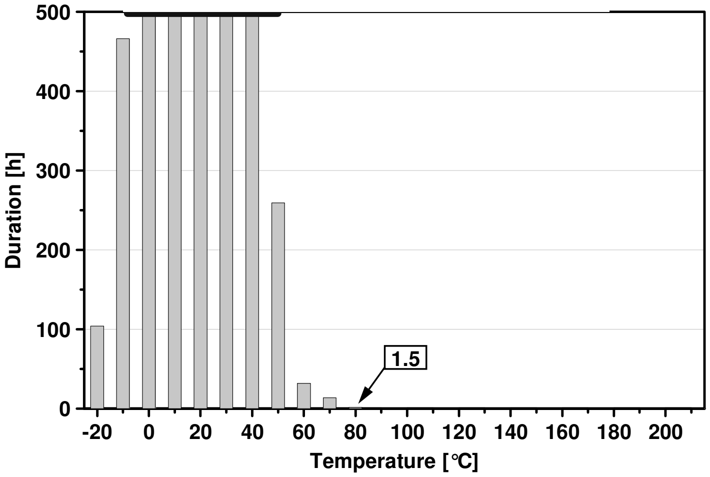

Fig. 4. Temperature Histogram of the Glazing (collector in the system)

As was anticipated, the cover of the dry collector showed a significantly higher temperature level than in the collector in the system (Figure 5). The surface temperature of this part was above 55 °C for 585 h in the considered measurement period, the maximum temperature was 86 °C.

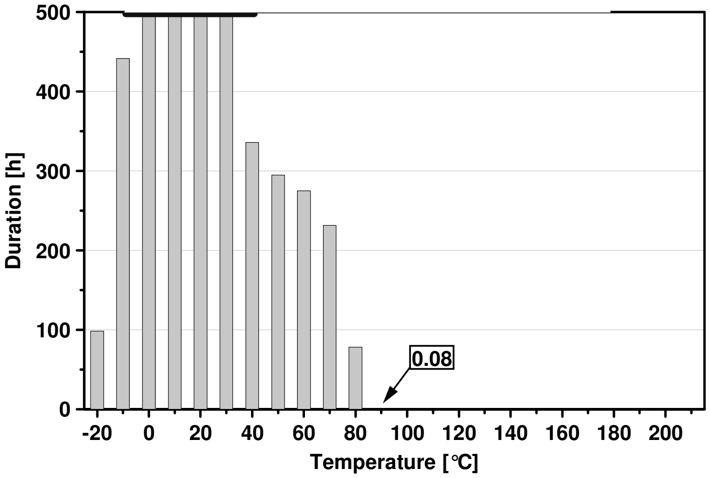

Fig. 5. Temperature Histogram of the Glazing (dry collector).

For the investigation of the frame temperatures, several sensors were positioned on the inner surface of the aluminium frame by rivets, outside the collector insulation. The sensor used for the analysis of the collector in the system was located at the upper side of the collector near the outlet (cf. Figure 1; right picture). Hence, there is obviously an influence of the flow pipe by heat conduction in the aluminium frame causing the highest temperatures at the frame. The temperature load increased up to 79 °C, but reached mostly only temperatures below 65 °C, influenced by the ambient air (Figure 6).

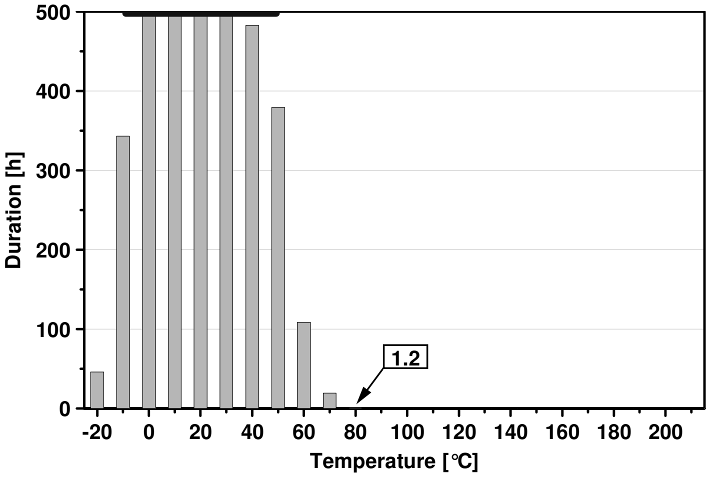

Fig. 6. Temperature Histogram of the Frame (collector in the system).

The temperature sensor in the dry collector was positioned central at the upper part of the frame. The peak temperatures were slightly lower because there was no influence of a hot outlet pipe despite the higher absorber temperatures (Figure 7).

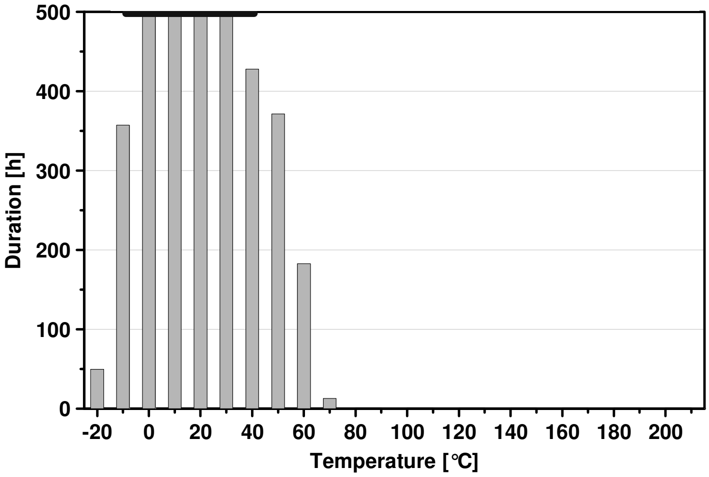

Fig. 7. Temperature Histogram of the Frame (dry collector).

2.3. Detailed Field-Testing Results

Apart from the maximum collector temperature, the dynamic behaviour of the components is of major interest. On the one hand, rapid temperature changes must be considered in the collector design, due to different linear thermal expansion of parts and materials. On the other hand, the response time for temperature reducing measures in the solar-thermal system can therewith be estimated.

Figure 8 demonstrates the outstanding dynamic behaviour of the dry absorber in comparison to the moderate response of the casing. The temperature of the absorber increased by 125 K (09:30...10:45 a.m.) and decreased by 121 K (10:45...12:00 a.m.) in a range of only 2.5 hours. During cooling down, the temperature decrease was decelerated by short sunshine periods (11:00...11.30 a.m.), so that a faster temperature decrease would still have been possible. The temperature of the casing increased from 12 °C up to only 35 °C, while the ambient air temperature was between 9 °C and 14 °C.

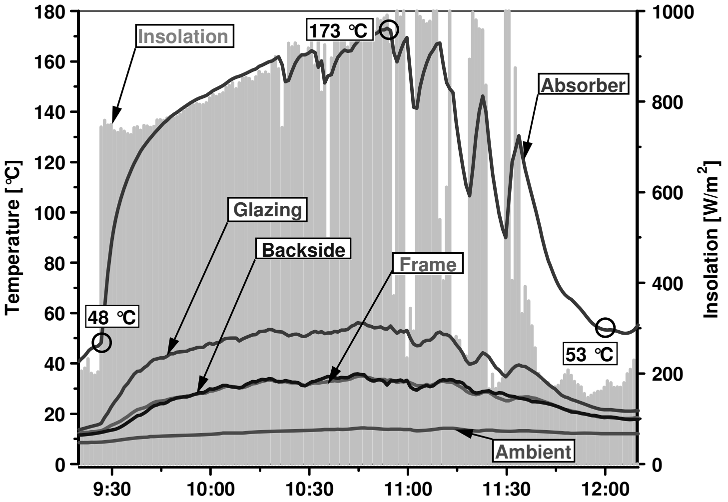

Fig. 8. Temperature Profile of the Dry Collector in September

There is also high absorber dynamics at very low ambient temperatures in winter. The temperatures of the parts of the dry collector were below 5 °C on a cloudy day in December with an ambient temperature near freezing. After clearing up of the sky, the insolation and the absorber temperature were rising. The temperature of the absorber increased by 140 K in 45 minutes whereas the cover sheet temperature increased only by 45 K. Hence, the absorber showed very dynamic behaviour, the glazing had a medium feedback and the frame and backside had a very low feedback.

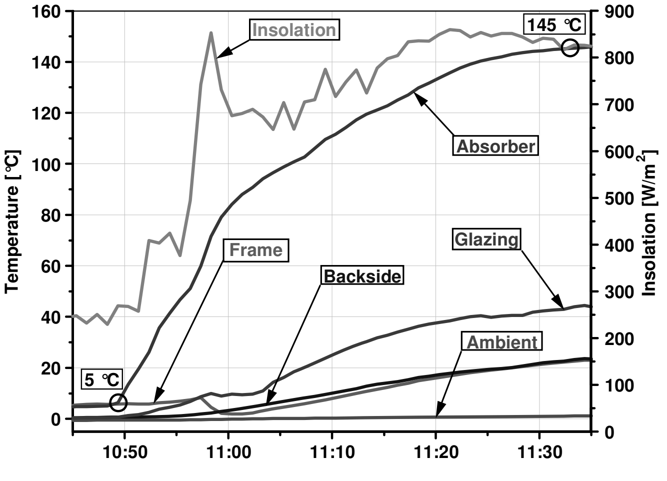

Fig. 9. Temperature Profile of the Dry Collector in Winter (December)

Especially at low ambient temperatures, there is a large difference between thermal behaviour of the absorber and the housing. When designing a solar-thermal collector, the differences between the thermal expansions of the parts must be considered.

2.4. Simulation

A dynamic simulation model of the field-testing collector was developed for the CARNOT blockset in the MATLAB/SIMULINK environment. The three-node model describes the thermal capacities of absorber, cover and fluid. It is used to calculate the temperatures of these components and of the backside insulation on the outer and inner surface, in order to investigate the temperatures and evaluate the model under field-testing conditions.

The measured data of the flow and the weather are used for the validation of the model. Therefore, the collector array and the dry collector were built up in simulation models.

Figure 10 and Figure 11 show the comparison of glazing temperatures in field-testing and simulation for 6. Aug. 2009.

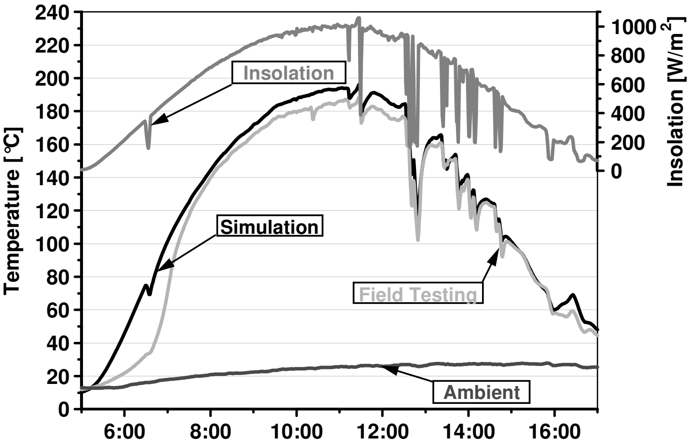

Fig. 10. Absorber Temperatures in Field-Test Measurement and Simulation of the Dry Collector (6. Aug. 09).

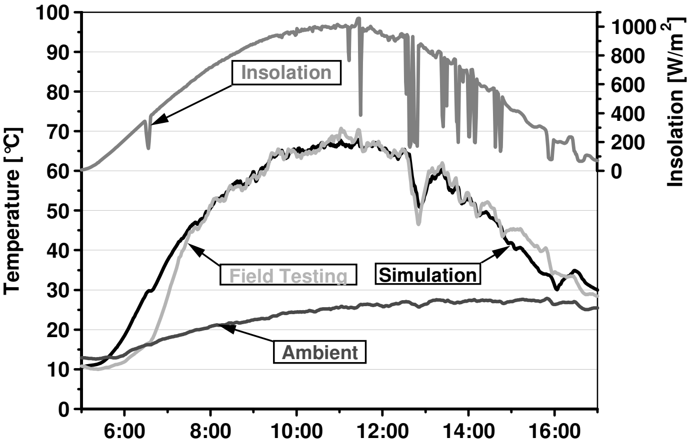

Fig. 11. Glazing Temperatures in Field-Test Measurement and Simulation of the Dry Collector (6. Aug. 09).

The model parameters can be varied to represent different collector and system configurations. Hence, the model provides the possibility for investigations of solar-thermal system, e.g. adapted to polymer needs by using overheating protection measures, as well as for the deduction of requirements definitions for polymeric materials.

References

[1] C. Reiter, C. Trinkl, W. Zörner, H. Müller, F.-D. Treikauskas (2009). Polymeric Solar-Thermal Collectors: Requirements, Concept Development and Feasibility Evaluation. Proceedings estec2009, ESTIF, Munich.