Profiled Glass Solar Façade with Integrated Heat Pipe Absorber – Experimental Evaluation of Prototypes

Maik Kirchner, Bert Schiebler, Tobias Wehmeier and Federico Giovannetti

Institute for Solar Energy Research, Hamelin (Germany)

Abstract

The paper presents the development of a solar thermally activated U-shaped profiled glass mainly intended for the use in façades of non-residential buildings. The activation is achieved by inserting a metallic tube-and-sheet solar absorber provided with heat pipes into the air gap of a double-shell profiled glass. We manufacture specimen with different design and size and investigate their performance and thermal behavior by means of indoor and outdoor experiments. For 2 m² modules we report zero-loss efficiencies η_0 up to 0.59 and heat loss coefficients a_1 between 3.8 and 5.8 $Wm^{-2}K^{-1}$ as well as a_2 between 0.012 and 0.03 $Wm^{-2}K^{-2}$. To analyze thermal comfort issues a small demonstration plant was installed in the south façade of a production hall consisting of profiled glass and was monitored under stagnation conditions over a period of one year. The maximum surface temperatures recorded on the room-side of the module are usually higher than those of standard non-activated glass in winter, but comparable in summer.

Keywords: Building integration, solar thermal collector, heat pipes, profiled glass

1. Introduction

Achieving the ambitious European climate policy goals requires the exclusive construction of nearly zero-energy buildings, significantly higher renovation rates and a much greater use of renewable energies to cover the heat demand (EU, 2021).

The use of solar energy for space heating, domestic hot water and the supply of industrial processes offers a concrete possibility to meet these requirements. Previous approaches are mainly limited to the residential sector and are based on the installation of solar thermal collectors on the roofs of buildings according to the additive principle (rarely on façades). This usually leads to low architectural acceptance and high costs, which has impaired a successful diffusion in the building practice so far (Cappel et al., 2014; Mauer et al., 2020).

An alternative approach to counteract this problem is the solar thermal activation of existing components of the building envelope by modifying and adapting their structure. This approach can enable cost reductions through synergy effects, as materials for mounting systems as well as for building claddings can be saved. In addition, a high degree of design freedom and high-quality architecture can be achieved. So far, different R&D works have been carried out on this topic in the last years (Giovannetti et al., 2016; Mauer et al., 2017; Denz P.-R. et al, 2018; Weiland et al., 2019; Frick et al. 2021), but such products are still hardly available on the market. The known solutions are either too complex or have very high investment costs. There is an urgent need for new architectural and technical building concepts and products that can extend the range of available options for architects, planners and builders in both new and existing residential and non-residential buildings.

In the "Solar Profil" project presented here, we evaluate a new approach in cooperation with the companies Flachglas Sachsen GmbH and Eilenburger Fenstertechnik GmbH.

Aim of the project is the development of a façade system consisting of profiled glass with integrated solar absorber, for the active use of solar energy for heat generation (space heating, domestic hot water or supply of industrial processes).

By combining solar absorbers and profiled glass of different types, the best compromise between energy generation, visual / thermal comfort, aesthetics and cost should be achieved.

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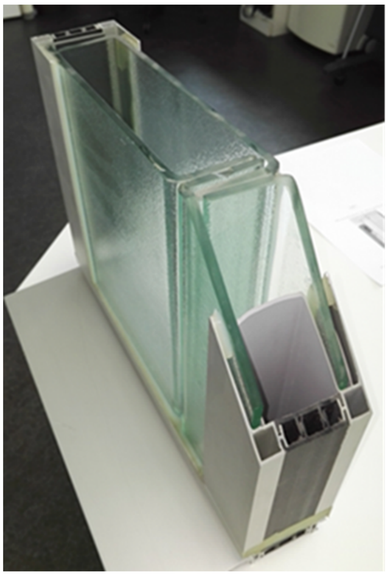
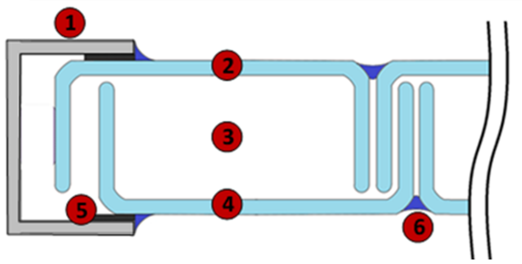
2. U-shaped Profiled Glass

U-shaped profiled glass is produced from cast glass with a thickness of 6 to 7 mm, width between 230 to 500 mm and length up to 7 m. The surface can be structured, as well as clear. Due to their statically favorable U-shape, cost-efficient single and multiple glazed façades with large spans without transom can be realized. The individual glasses are attached using an aluminum frame. The glasses are inserted individually into the frame. Designed as a multi-layer, coated system, U-values of up to 1.1 W / (m²K) can be achieved (assembly with low-emissivity coating). Figure 1 shows the model and schematic design of a double-shell profiled glass façade system.





1: aluminum frame

2 and 4: U-shaped profiled glass

3: air gap (integration of the absorber)

5: lining tape

6: silicone

Fig. 1: Model (left) and schematic representation (right) of a façade system consisting of double-shell U-shaped profiled glass

Profiled glass is mainly used for industrial and commercial applications but also for residential and public buildings such as schools, theaters and museums. Usually there, where a large amount of daylight is desired or required. However, the experience shows that the supply of daylight is often higher than the demand and that the requirements for visual comfort can be still fulfilled even by significantly reducing the transparency of the building envelope. Depending on the building typology and use, it is necessary to check what percentage of the façade is available for the active use of solar energy.

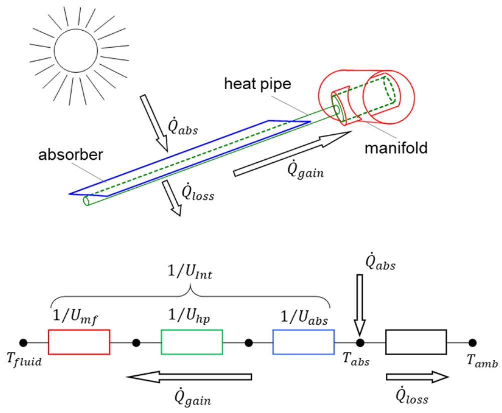
3. Solar-activated U-shaped Profiled Glass

The development is based on the double-shell profiled glass façade system outlined above. The solar thermal activation is achieved by inserting a metallic absorber into the air gap between the two profiled glasses. Suitable spacers are provided to place and center the absorber in the gap so that contact between the absorber and the profiled glass is prevented. In the selection of geometry and materials of the spacer in addition to the cost, in particular the requirements on temperature stability and aesthetics must be considered. The heat transfer between the solar absorber and the solar circuit takes place via heat pipes, which are thermally coupled to the solar circuit by means of a dry connection. Compared to direct flow collectors, collectors with heat pipes exhibit the following advantages, especially for façade applications and specific for the integration in profiled glass:

- Compatibility with the modular assembly of the profiled glass system
- Significantly smaller amount of heat transfer medium (approx. factor 100) and thus lower weight
- Simpler hydraulic circuit and thus easier integration into the façade system
- Low pressure drop and easy venting
- Possibility to set the maximum temperature of the system by properly dimensioning the heat pipe (type and amount of the heat transfer medium) to avoid overheating.

In addition to the advantages listed, one significant disadvantage has to be mentioned: Heat pipes represent an additional thermal resistance between the solar absorber and the solar circuit. The efficiency of collectors with heat pipes is lower than that of collectors with direct flow. For an efficient use of this advantageous technology, the thermal connection to the manifold is particularly important.

Based on the experience at the ISFH with already completed or ongoing projects on the use of heat pipes in solar thermal applications, the theoretical potential of the zero-loss efficiency value was determined according to the thermal equivalent circuit diagram shown in Figure 2. Typical values of the individual heat transfer coefficients at the absorber U_{abs}, the heat pipe U_{hp} and the manifold U_{mf} are used for the further calculation. The manifold heat pipe coefficient typically ranges between 5 W / K for manifolds with plug-in sleeve and 10 W / K for hydro-formed manifolds with clamp connection. The heat pipe heat transfer coefficient with an organic working fluid is between 2 and 4 W / K (depending on the condenser temperature and the thermal output), whereby heat pipes with water as working fluid can reach heat transfer coefficients above 15 W / K (Jack et al., 2013). In this case, heat pipes with an organic heat transfer medium are used in the first step. This makes it possible both to limit the maximum temperature that occurs at the manifold (avoidance of stagnation damage) and to guarantee a frost-free operation of the system (Schiebler et al., 2018).



$$\eta_0 = (\tau\alpha)_{eff} \cdot \frac{U_{Int}}{U_{Int}+U_{loss}} \qquad \text{(eq. 1)}$$

Fig. 2: Thermal equivalent circuit diagram of an absorber strip including the manifold. Color design of the individual heat transfer coefficients (manifold U_{mf}, heatpipe U_{hp}, absorber U_{abs}); heat loss coefficient U_{loss}; internal heat transfer coefficient U_{Int}; absorbed heat flow $\dot{Q}_{abs}$; useful heat flow $\dot{Q}_{gain}$; heat loss flow $\dot{Q}_{loss}$; zero-loss efficiency η_0 as a function of the effective transmission-absorption product $(\tau\alpha)_{eff}$ the internal heat transfer coefficient and the heat loss coefficient.

Assuming a specific absorber heat transfer coefficient U_{abs} of 30 W / K, a heat loss coefficient of 5 W / (m²K) typical for flat-plate collectors (in relation to the absorber area) and a transmission-absorption product of 0.83 (solar transmittance glass 0.86, solar absorptance 0.95), the zero-loss efficiency value depends on the heat pipe and manifold heat transfer coefficients. As shown in Figure 3, under the assumptions made, zero-loss efficiencies up to approx. 0.75 are possible. To achieve this value, a manifold with a specific heat transfer coefficient of at least 15 W / K and a highly performing heat pipe with a specific heat transfer coefficient greater than 10 W / K must be used. For the profiled glass collector, an optimization of the manifold and condenser geometry is carried out within the scope of this work in order to achieve higher specific heat transfer coefficients compared to the geometries customary on the market.

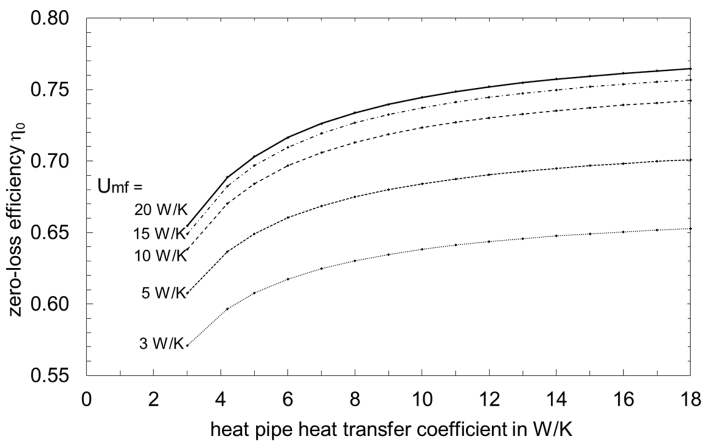


Fig. 3: Zero-loss efficiency η_0 as a function of the manifold and heat pipe heat transfer coefficients (U_{mf} and U_{hp}) with an absorber heat transfer coefficient (U_{abs}) of 30 W / K, heat loss coefficient (U_{loss}) of 5 W / (m²K) and an effective transmission-absorption product ($(\tau\alpha)_{eff}$) of 0.827 (in relation to the absorber area per heat pipe of 0.132 m²)

First investigations focus on solar absorbers consisting of standard metal sheets provided with spectrally selective or non-selective coatings. By using colored coatings, the arrangement and the nature of the absorber sheets, a high architectural design freedom can be achieved (e.g. use of perforated sheets). This relates on the one hand to the aesthetic appearance and on the other hand to the supply of daylight to the building. Figure 4 shows schematically exemplary possibilities for controlling the daylight supply.

Fig. 4: Perforated absorber sheets to increase the daylight supply (left); Façade design options with colored absorbers and alternating arrangement of transparent, conventional and opaque, solar-active U-shaped profiled glass (right)

4. Experimental Evaluation of Solar-active U-shaped Profiled Glass Modules

Based on the theoretical consideration of the specific heat transfer coefficients, different large-format, solar-activated u-shaped profiled glass modules were manufactured and experimentally investigated. Figure 5 shows the schematic design and a large-format sample.

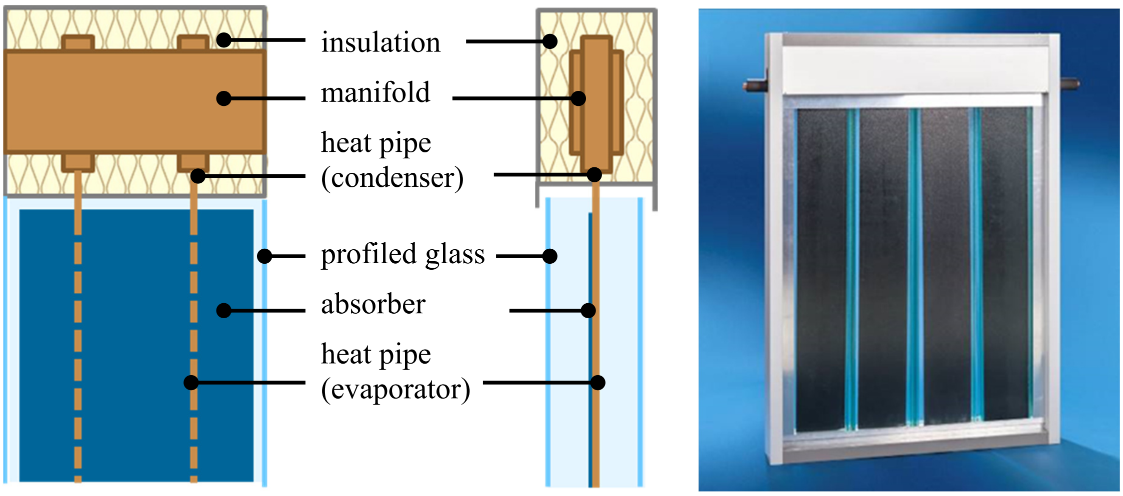


Fig. 5: Schematic representation of the façade profile with integrated, solar thermal absorber (left) and a test façade module (right; variant with non-selective black absorber)

Efficiency parameters as well as the maximum temperatures occurring in the module and on the glass surfaces under stagnation conditions were determined on a 2 m² profiled glass sample under artificial irradiation according to the ISO 9806 Standard (ISO, 2018). These temperatures play an important role in the development both with regard to the resistance of materials and components and to the question of thermal comfort in the interior (radiant heat of the glass interior surface). The façade module was examined in different configurations. In the individual versions, two different absorbers (selective and non-selective), two different front profiled glass (ferrous and low-iron variants) and two measures to reduce rear heat losses (low-emitting coating; additional 3 cm thick insulation on the rear of the absorber) were tested. A total of four different variants were examined, which are shown schematically in Figure 6 to illustrate the respective structure.

The different configurations led to zero-loss efficiencies η_0 related to the aperture area in the range from 0.51 to 0.59 as well as to heat loss coefficients a_1 in the range from 3.8 to 5.8 W / (m²K) and a_2 from 0.01 to 0.03 W / (m²K²). The results of the specific variants are shown in Table 1.

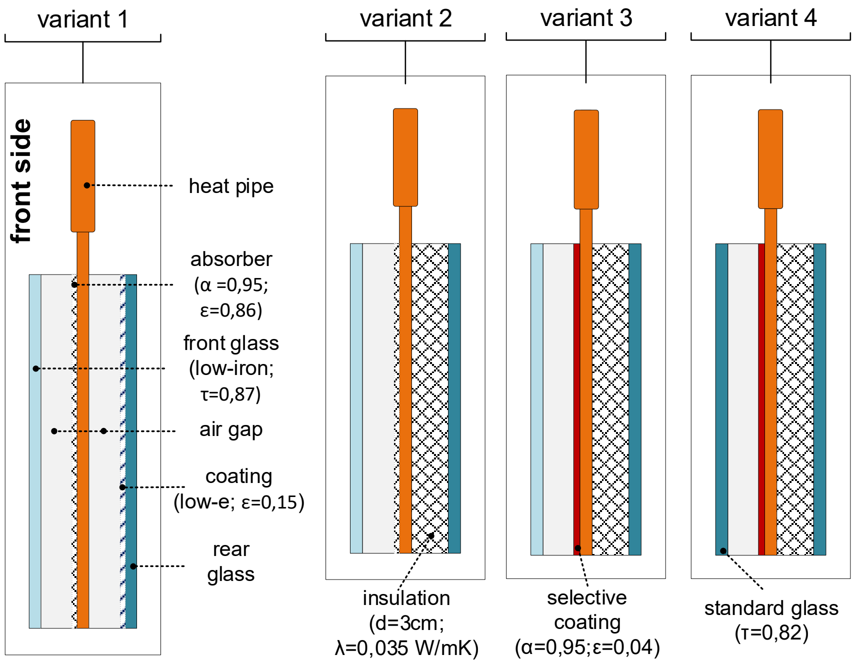


Fig. 6: Schematic sectional view of the investigated variants with technical data of the components

Tab. 1: Efficiency parameters of the investigated variants related to aperture area

Variant	Description	η_0	a_1[W/(m²K)]	a_2 [W/(m²K²)]
1	front glass: τ=0.87 absorber: α=0.95; ε=0.86 rear glass: low-e coating ε=0.15	0.51	5.8	0.030
2	front glass: τ=0.87 absorber: α=0.95; ε=0.86 rear insulation: 3 cm; λ=0.035 W/(mK)	0.54	5.6	0.017
3	front glass: τ=0.87 absorber: α=0.95; ε=0.04 rear insulation: 3 cm; λ=0.035 W/(mK)	0.59	3.8	0.012
4	front glass: τ=0.82 absorber: α=0.95; ε=0.04 rear insulation: 3 cm; λ=0.035 W/(mK)	0.54	3.8	0.012

The comparison of variant 1 to variant 2 shows that thermal insulation applied to the rear side of the absorber can reduce heat losses and thus also improve the zero-loss efficiency. The heat losses are further reduced in variant 3 by using a spectrally selective, low emissivity absorber coating, so that a zero-loss efficiency of 0.59 related to the aperture is achieved. The reported value is still significantly lower than those of a standard flat plate collector (0.75 – 0.80). This depends on the one hand, on the lower solar transmittance of the low-iron cast glass used (0.87), compared to typical values of low-iron flat glass (0.90) and, on the other hand, on the effective absorber area of the profiled glass collector. The absorbers only occupy around 80 % of the aperture, so that the remaining 20 % is not used for the active production of thermal energy but still available for daylight supply. This aspect must be considered for a holistic performance assessment of the façade system, as this type of solution is typically used in buildings with a high demand for daylight. The first system simulations on a reference building show that visual comfort is not adversely affected if up to 50% of the façade area is covered with solar-activated u-shaped profiled glass modules.

In order to evaluate the performance of the manifold / heat pipe configuration used and compare it to the state-of-the-art, the results should be referred to the absorber area. Under this assumption, for example, variant 3 has a zero-loss efficiency of 0.75. Considering the theoretical parameter study shown in Figure 3, this result proves that the manifold and heat pipe solutions implemented for the manufactured modules ensure very good heat transfer from the absorber to the solar circuit fluid.

To estimate the maximum expected thermal load occurring on the individual components and on the glass surface temperatures during operation, the façade modules were exposed to artificial radiation over a period of 5 hours. To compare the configurations with each other, the standard stagnation temperature (irradiance of 1000 W / m² and 30 °C ambient temperature, no wind) of the individual surfaces was calculated based on the extrapolation method according to DIN 4757 (DIN, 1995). This resulted in maximum absorber temperatures for the non-selective variant 2 of 133 °C and for the variant 3 with selective absorber of 183 °C. These conditions lead to a room-side glass surface temperature of 45 °C for variant 2 and 52 °C for variant 3 respectively.

To analyze the performance of larger elements usually implemented in real buildings, a 4 m² (4 m x 1 m) module was manufactured with a non-selective absorber (α = 0.95; ε = 0.86) provided with rear-side insulation as for variant 2 (Table 1), but exhibiting a ferrous front glass (τ = 0.82). The measurement was carried out by means of an outdoor sun tracker. In our first measurements at normal incidence angle we reported a zero-loss efficiency η_0 of 0.44. The large difference of 10 percentage points compared to the variant 2 of the 2 m² module results both from the lower solar transmittance of the front glass ($\Delta\tau$ = 0.05) and from a lower internal thermal coefficient due to the larger absorber surface and thus to the correspondent thermal power transferred per heat pipe. The size-dependent performance of the module has to be taken into consideration for the design and assessment of the specific façade solution.

Fig. 7: Large test façade module during the measurement on the sun tracker at ISFH (4 m x 1 m)

5. Evaluation of the Module in a Real Building

In order to evaluate the constructive aspects of the façade integration and the behavior of the new development under real installation conditions, a demonstration module according to variant 3 was installed in the façade of a production hall, featuring double-shell U-shape profiled glass. We measured the surface temperatures of the individual components of the module, focusing on the maximum temperatures occurring on the room-side glass surface, which are directly compared with the temperatures of a reference, non-activated module of the existing façade. Main goal of this investigation was the assessment of the impact of the solar activated module on the thermal comfort as a consequence of the higher solar absorption, both under summer and winter conditions. For this purpose, the solar module is operated during the entire exposure phase under stagnation conditions (unfilled solar circuit or collector). The temperature on the room-side glass surfaces and on the absorber is measured by using a Pt-100 chip sensor placed at 2/3 of the aperture height. In addition, the hemispherical irradiance on the façade (south-east orientation, azimuth angle = -54°) as well as the outdoor and indoor air temperatures are recorded. Figure 8 shows both the reference (a) and the demonstration solar module (b) integrated into the façade of the production hall.

Fig. 8: Façade-integrated, solar-activated profiled glass module (b) and reference profiled glass module (a), with sensors for recording the temperatures and hemispherical radiation (glass surface and absorber temperature placed at 2/3 of the aperture height)

Figure 9 shows the frequency distribution of the room-side glass surface temperature of the solar-activated and reference profiled glass modules over the measurement period from May 20th, 2020 to June 30th, 2021. During this period, the data were recorded with a measurement interval of one minute for a total time of 9382 hours. The respective monthly maximum and minimum values of the recorded temperatures as well as the hemispherical irradiance are given in Figure 10.

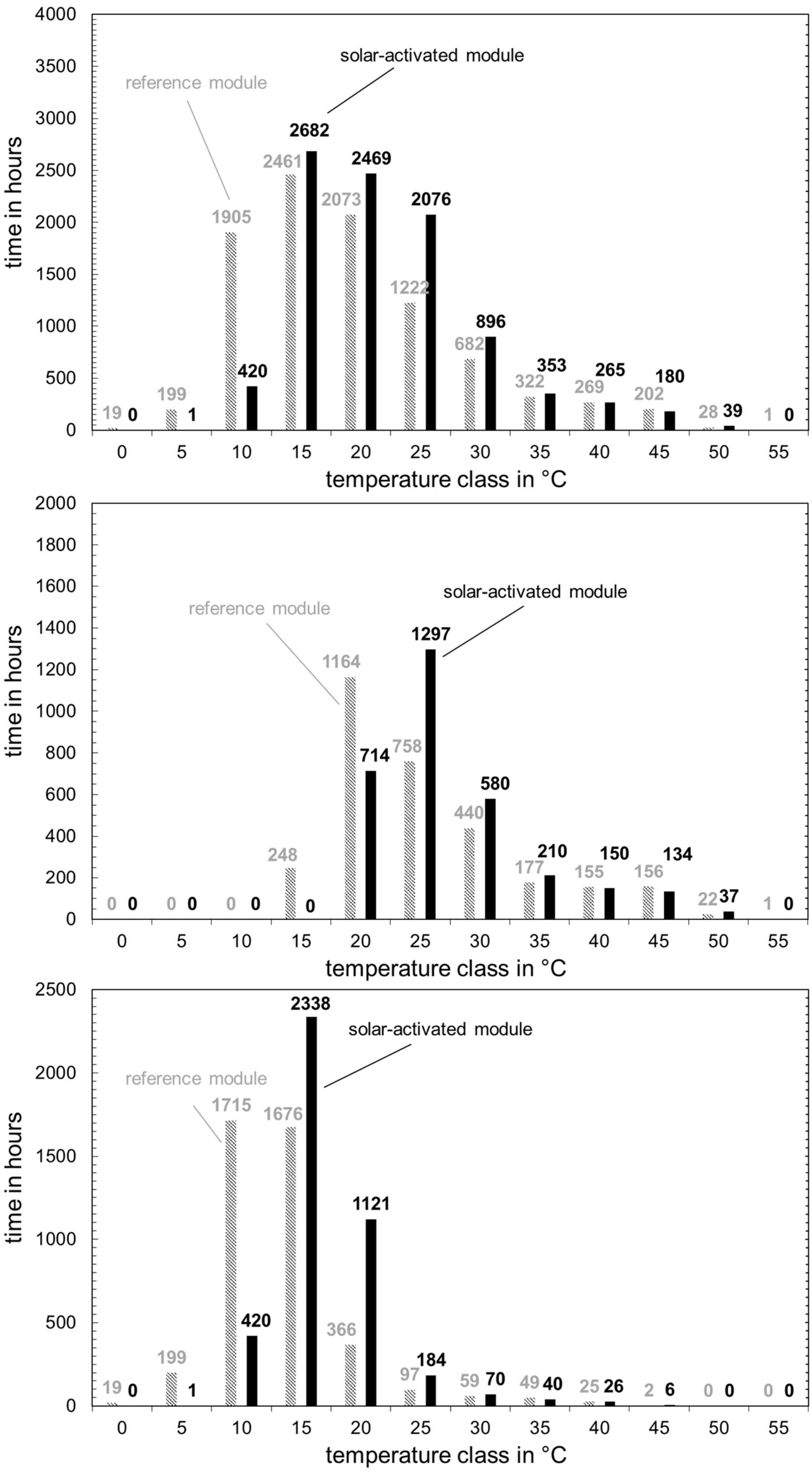


Fig. 9: Frequency distribution of the room-side glass surface temperature of the solar-activated and the reference profiled glass module (top: entire exposure period; middle: 20.05.2020 to 30.09.2020; bottom: 01.10.20 to 31.03.2021). The temperature class refers to an interval of ± 2.5 ° C around the class value

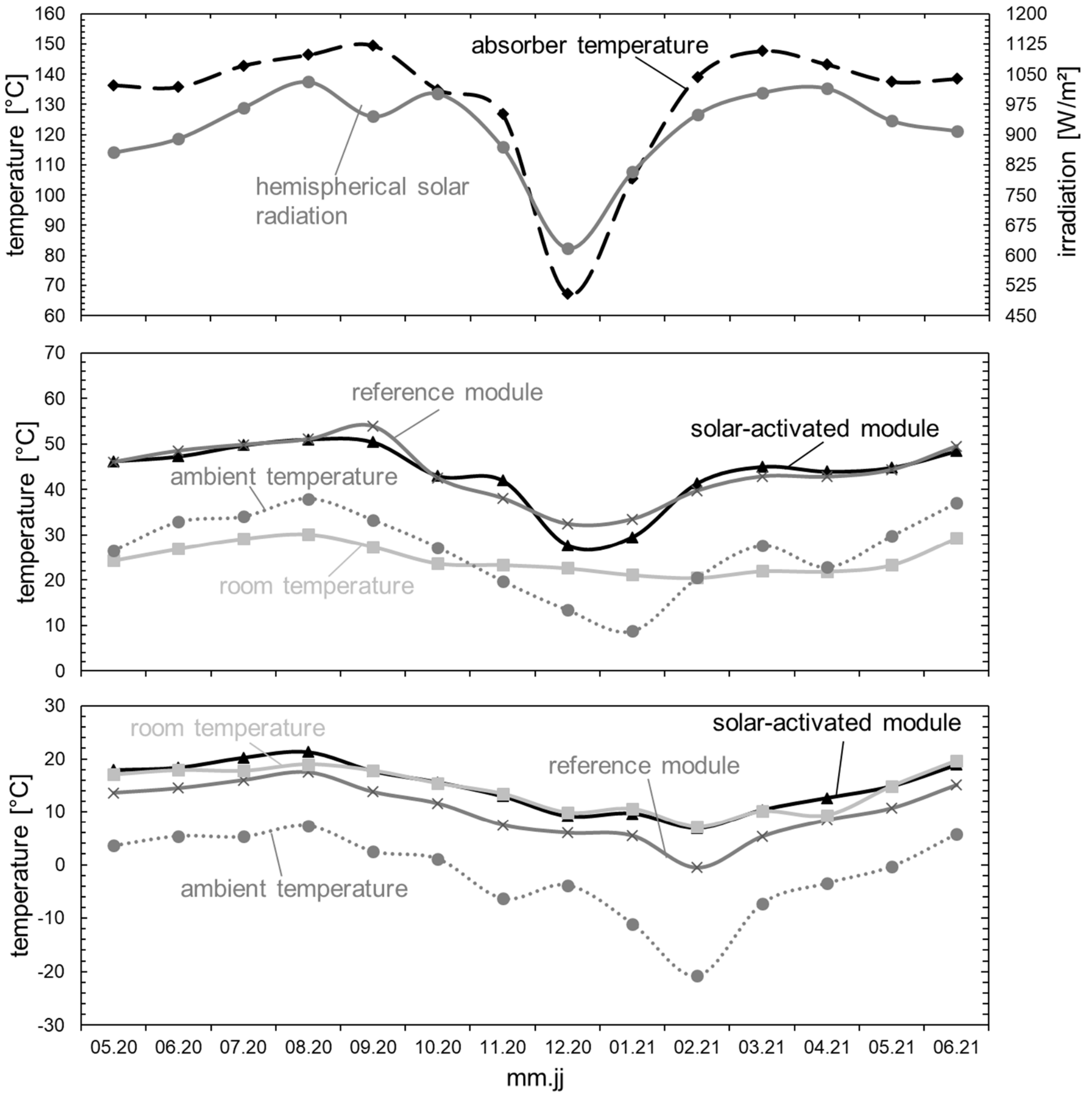


Fig. 10: Maximum mean values (1-minute resolution) of the absorber temperature, the room-side glass surface temperature of the reference as well of the solar activated module, the ambient and room temperature and the hemispherical irradiance on the façade for the respective month during the measurement period from 05.2020 to 06.2021 (top and center). Minimum mean values of the glass surface temperature of the reference and solar modules, the ambient and room temperatures (bottom).

The frequency distribution over the measurement period as well as the monthly maximum values show that the investigated solar thermal module does not lead to an increased thermal load for the interior of the building in the summer months in comparison to the reference module. It should be noted that maximum absorber temperatures up to approx. 150 °C were recorded in the façade installation, which are 30 K lower than the measured stagnation temperature of the modules under test conditions. The temperature frequency distribution for the months October to March as well as the monthly minimum values show, on the other hand, that the module has higher temperatures compared to the reference module. This results in a lower effective U-value, which has a positive effect on the transmission heat losses of the building. For a more detailed assessment with respect both to comfort and performance, real operation conditions referred to specific applications (domestic hot water preparation, space or industrial heating) have to be taken into consideration. For this purpose, building simulations based on the experimentally determined efficiency parameters of modules with different design are planned.

6. Acknowledgments

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