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Prototype Development and Construction of a Façade-integrated Solar Thermal System for Domestic Hot Water Preparation

Sven Stark[1]*, Natalie Gohl[1], Anja Loose[1] and Harald Drück[1]

[1] Research and Testing Centre for Thermal Solar Systems (TZS),

Institute of Thermodynamics and Thermal Engineering (ITW),

University of Stuttgart, Pfaffenwaldring 6, 70550 Stuttgart, Germany

*Corresponding author, E-mail: stark@itw.uni-stuttgart.de

Abstract

Solar thermal systems with roof-mounted collectors and basement-located heat stores represent a mature technology for solar space heating and domestic hot water preparation in residential buildings. However, due to the limited available roof area, an increase of the solar fraction is often not possible. Especially in case of multi-story residential buildings with a low ratio of roof area to living area and dwelling units, the façade-integration of solar thermal components seems to be the only solution for covering considerable parts of the heat demand (> 50 %) by solar energy.

Placing solar collectors in front of the façade is the most common technique when conducting building-integrated solar thermal (BIST), but actually more ambitious approaches in this field are needed for achieving a real architectural and technical integration. So-called multifunctional solar thermal façade components combine the features of a standard building façade such as thermal and noise insulation and protection against environmental influences with the functions of a solar thermal system, i.e. generation, storage and distribution of solar heat.

In this paper the development and construction of a prototype of such a multifunctional solar thermal façade element is presented. The façade element comprises a complete solar thermal system for the preparation of domestic hot water and it consists of a transparent thermal insulation as energy-harvesting component, a hot water tank as absorber and heat store, different types of thermal insulation and the entire hydraulic circuitry (except for the controller) for the supply of the hot water to the dwelling unit. Besides the description of the technical details and characteristics of the different components, this paper will focus on different options for the integration of the multifunctional solar thermal façade element into the building envelope. Furthermore, approaches for envisaged laboratory and outdoor testing will be presented in this paper.

Keywords: building-integrated solar thermal (BIST), multifunctional façade element, solar thermal system

1. Introduction

Compared to roof-mounted collectors the solar thermal heat generation in a façade offers the advantage of a more equal distribution of solar gains over the year for regions far away from the equator. On the one hand the higher ratio of solar gains in winter leads to a better solar coverage of space heating demand, while on the other hand collector stagnation due to overheating is reduced due to the greater angle of incidence in summer. Furthermore, the larger available area of the façade compared to the limited roof area allows for achieving a higher solar fraction of the total heat demand of the dwelling, which is of particular relevance in case of multi-story residential buildings [1] [2].

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However, the façade-integration of solar thermal components also poses a number of challenges. A special difficulty that has to be overcome is the often unsatisfying architectural integration of collectors placed in front of the existing façade. Because of the visibility of the collectors their design and integration has to be well-adapted to the rest of the façade to form an appealing building envelope [2]. Furthermore, functional aspects of the integration into the façade have to be considered. This means that the solar thermal components should additionally take over or at least support the functions of a standard building façade, namely to act as a thermal and noise insulator and to protect the interior of the building against the environmental influences [1].

An innovative and ambitious approach for using the façade as a solar active part of the building is currently being developed within the research project "MultiKomp-I" at the Research and Testing Centre for Thermal Solar Systems (TZS) of the Institute of Thermodynamics and Thermal Engineering (ITW) at the University of Stuttgart. The project aims at developing so-called multifunctional solar thermal façade elements that combine the features of a standard building façade such as thermal and noise insulation and protection against environmental influences with the functions of a complete solar thermal system, i.e. generation, storage and distribution of solar heat. As far as possible, all these functions are to be united in one compact façade element to save space and to reduce costs compared to the conventional approach of installing solar collectors only in the façade. The project MultiKomp-I (full title: "Development of multifunctional solar building components, Phase I: Basic research activities") is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi), based on a decision of the German Bundestag by Projektträger Jülich (PTJ) under grant number 0325985A.

Up to now, a first prototype of such a multifunctional solar thermal façade element has been built and the construction of a second prototype is currently prepared. The following chapters deal with the construction and characteristics of the first prototype, focus on possible ways of integrating the façade element into the building envelope and finally present the envisaged laboratory and outdoor testing of the prototype.

2. Prototype development

In the first phase of the project about 15 different theoretical concepts for multifunctional façade elements with a different scope of functions such as space heating, space cooling and domestic hot water preparation were elaborated by combining state-of-the-art as well as innovative technologies for the relevant tasks of the façade and the solar thermal system. A selection of these technologies that can be used in such façade elements is given in the following:

- **solar heat generation**: solar collector with liquid heat transfer fluid, solar air collector, transparent thermal insulation, glass constructions (e.g. multiple glazing)
- **heat storage**: hot water store, heat store with phase change materials, thermochemical heat store, thermal activation of building components
- **heat insulation**: vacuum insulation panels, switchable heat insulation, conventional heat insulation (e.g. mineral wool, rigid foam insulation)
- **domestic hot water (dhw) preparation**: dhw heat exchanger integrated in the store, dhw store integrated in hot water store (tank in tank principle), external dhw heat exchanger
- **auxiliary heating**: electrical backup-heater, gas-fired instantaneous water heater, no backup heater
- **space heating system**: radiant panel heating (floor/wall heating), air heating system with heat recovery unit, passive heat supply.

As it was decided to build only two prototypes within the project the two most promising concepts had to be chosen based on the following simulation and evaluation measures:

- dynamic system simulations with TRNSYS for the most promising concepts, i.e. determination of the solar fractions for space heating and domestic hot water preparation dependent on a range of parameters such as element size, collector area, thermal insulation thickness, type of building, etc.

- scientific exchange with architects about the possibilities and challenges of building integration for the different concepts; both, with regard to technical and aesthetical aspects
- scientific exchange about the feasibility of using thermochemical stores for the façade elements
- evaluation and ranking of the different concepts according to other criteria, e.g. expected costs, aesthetics, level of innovation, thermal comfort of the dwelling unit.

The details of these studies as well as the results are not treated in this paper, but can be found in [1] and [3 - 5]. The concept of the façade element finally chosen and presented in this paper is illustrated in Fig. 1.

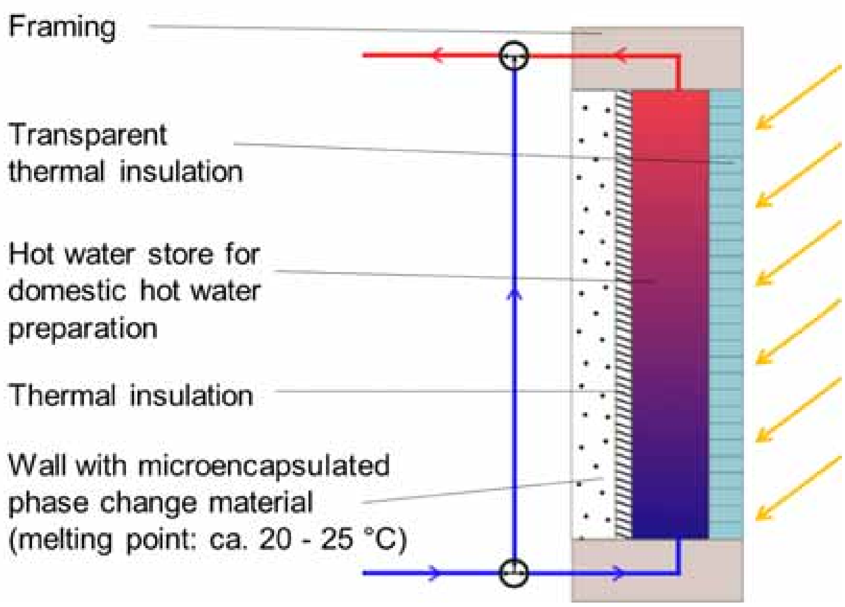

Fig. 1: Concept of the multifunctional solar thermal façade element for domestic hot water preparation

The idea of this concept is to build a multifunctional solar thermal façade element that predominantly delivers heat for the preparation of domestic hot water and contributes solar heat for space heating only to a minor extent by means of passive heat supply. Furthermore, the façade element is supposed to have a relatively simple construction and to combine all components in one compact module.

These required specifications are realized by the concept shown in Fig. 1. The charging of a hot water store is carried out directly by the solar radiation passing a transparent thermal insulation and heating the outside-facing wall of the storage tank. The store itself is thermally insulated towards the interior room to reduce overheating in summer and towards the exterior by a transparent thermal insulation in order to minimize heat losses of the store to the ambience. For a further reduction of overheating of the interior room phase change material is incorporated into the wall construction, e.g. a metal or wood stud wall, behind the hot water store. The discharging process for domestic hot water preparation is carried out via an external heat exchanger, because direct discharging via the connection to the domestic hot water cycle does not allow an unpressurized hot water store and compared to an internal heat exchanger a higher discharging power is achieved by an external heat exchanger.

After the compilation of the required characteristics of the main components and the selection of the respective suitable products, the detailed planning and dimensioning for the construction of a prototype was carried out. The prototype was then built up within TZS/ITW and equipped with measurement instrumentation for the laboratory and outdoor testing.

In the following chapter the construction of the prototype is explained in detail. After this the building integration of such a multifunctional solar thermal façade element is treated and finally approaches for envisaged laboratory and outdoor testing are presented.

3. Construction of the prototype

3.1. Construction overview

In Fig. 2 the set-up of the prototype of the developed façade-integrated solar thermal system is shown in an exploded design drawing, while in Fig. 3 it is illustrated how the prototype looks like with all components integrated and covered with panels at the sides. The functions and the characteristics of the most significant components are explained in the following.

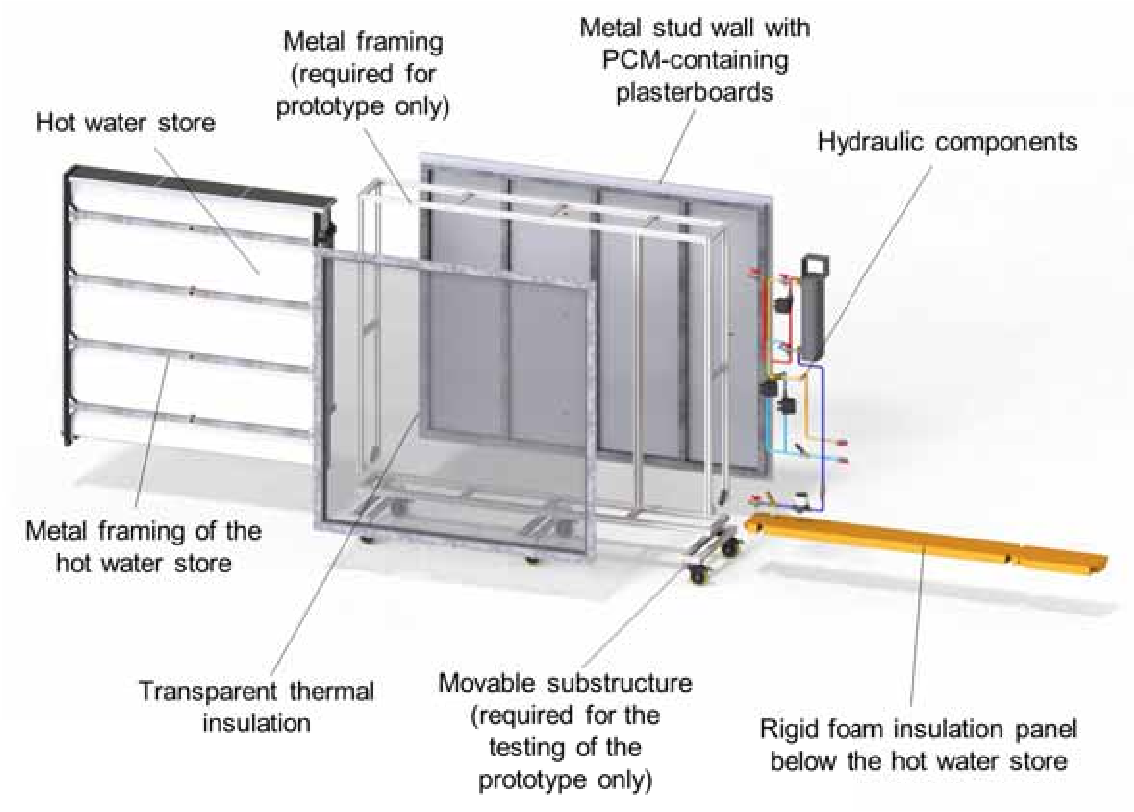

Fig. 2: Illustration of the set-up of the prototype built for laboratory and outdoor testing

Fig. 3: Front view of the prototype with cover panels

3.2. Transparent thermal insulation

As can be seen from figures 2 and 3, the transparent thermal insulation is located in front of the hot water store and its function is to let the solar radiation pass towards the wall of the hot water store by simultaneously reducing heat losses from the heat store to the outside. The type of transparent thermal insulation that was finally chosen after a comprehensive search for a suitable product is composed of two glass sheets with an aerogel filling (Fig. 4). Compared to other transparent thermal insulations it has a higher ratio of total energy transmittance to heat transfer coefficient, however, the relatively high weight can be seen as disadvantageous.

Type/composition: 2 glass sheets with aerogel filling

Length: 1,900 mm

Height: 1,900 mm

Total thickness: 46 mm

Total energy transmittance: 60 %

Heat transfer coefficient: 0.6 W/(m²∗K)

Weight: ca. 160 kg respectively 42 kg per m² façade area

Fig. 4: Characteristic data and photo of the transparent thermal insulation

The details of the mounting of the transparent thermal insulation are illustrated in Fig. 5. A Z-shaped metal profile is connected via screws to an aluminium profile which is part of the main frame (cf. Fig. 2) of the prototype. The transparent thermal insulation does not have direct contact with this metal profile which would be unfavorable due to the different coefficients of thermal expansion of glass and metal. It rather sits on a foam rubber and rubber profiles including lip seals are clamped between the transparent thermal insulation and the metal profile. In the mounting process the last step is to screw an I-shaped metal clamping profile with the rubber profile attached to the Z-shaped profile. The construction shown in Fig. 5 encloses all four sides of the transparent thermal insulation including the corners so that it is fixed and sealed all around.

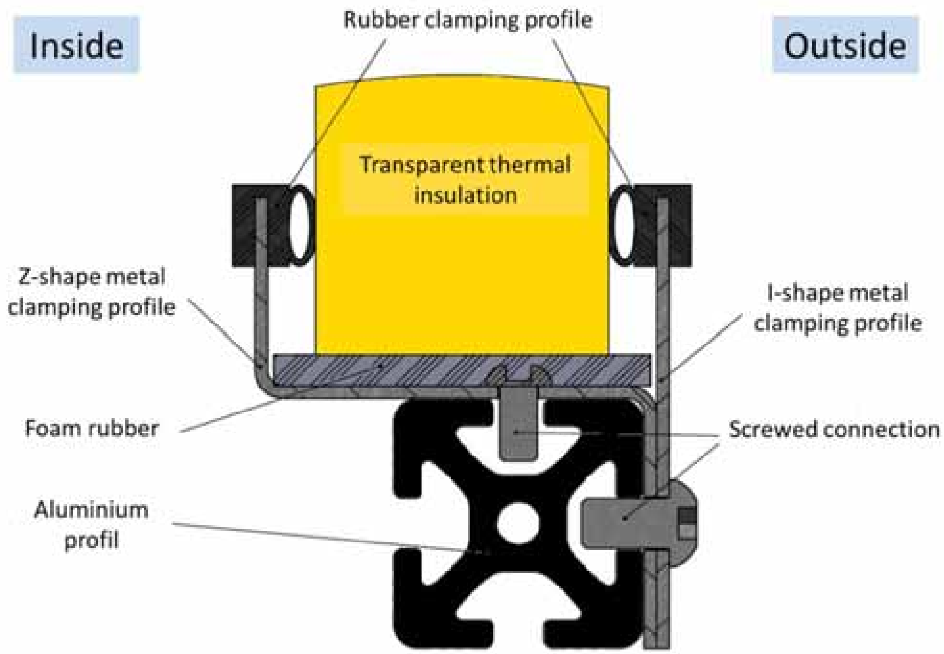

Fig. 5: Mounting details of the transparent thermal insulation

3.3. Hot water store and hydraulic system

When constructing the entire façade-integrated solar thermal system the aim was to use maximum space in the façade for the thermal energy storage and to easily integrate the hot water store into the façade element with regard to its shape. That is why a rectangular storage tank was chosen which is discharged via an external heat exchanger. Thus, except for the three thin metal deflector sheets integrated for preventing hydraulic short cuts (see Fig. 6) there are no other components inside the store. Furthermore, the store does not contain domestic hot water and can be operated without pressure. Nevertheless, framing of the store is needed (see Fig. 6), because otherwise the store made of polypropylene would suffer from deformation especially at temperatures above around 60 °C.

The front side of the hot water store is coated with a black absorber painting to enhance absorption of the solar radiation and to reduce thermal emissions from the store wall. For thermal insulation different materials were used as indicated in Tab. 1. Below the store there is a rigid foam insulation panel with a thickness of 60 mm, which sits on a 2 mm thick aluminium sheet for taking and leading the weight of the store to the module framing. Vacuum insulation panels were only integrated at the slim sides and on top of the store, because in the metal stud wall behind the store (see Fig. 2) the risk of damage was considered as too high.

Tab. 1: Characteristic data of the hot water store

Type and material:	unpressurized polypropylene hot water store
Shape and dimensions:	rectangular storage tank (1,800 mm x 1,800 mm, 172 mm thick)
Store volume:	approximately 400 litres
Weight:	ca. 130 kg (empty), ca. 530 kg (filled with water)
Charging/discharging:	direct charging via transparent thermal insulation
	indirect discharging via external heat exchanger
Fixing/stabilisation:	4 horizontal metal profiles at the front and back side of the store
	plastic framing profiles at the slim sides of the store
Thermal insulation:	rigid foam insulation panel (bottom)
	vacuum insulation panels (slim sides and top side)
	transparent thermal insulation (front side)
	aerogel felt as part of the metal stud wall (back side)
	expanded polystyrene (gaps at slim sides and back side)

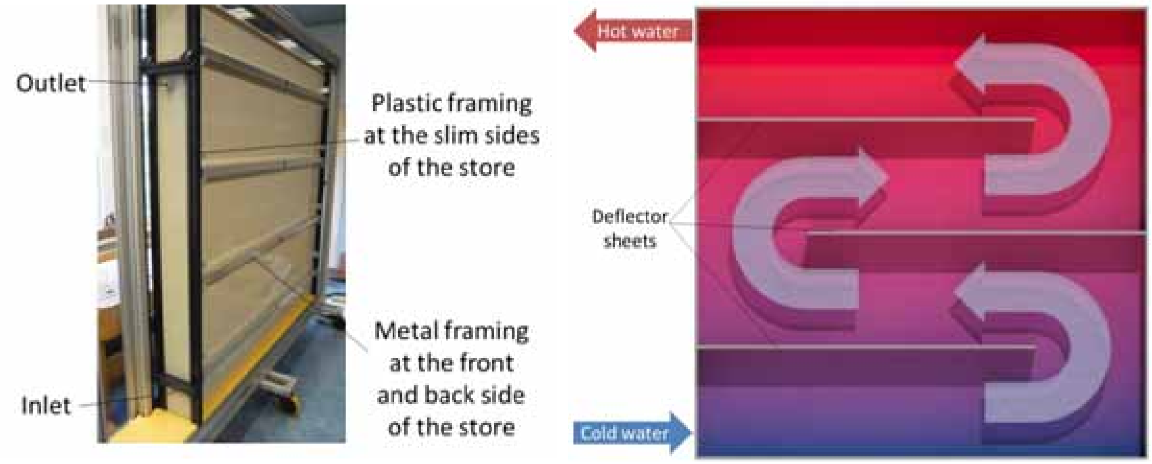

Fig. 6: Back side (left figure) and interior (right figure) of the hot water store

3.4. Metal stud wall, framing and substructure

As already mentioned in chapter 2, also passive heat supply to the interior of the building occurs. Hence, when the water in the store is hot this can lead to overheating in summer, which has to be prevented or at least minimized. Therefore, the metal stud wall behind the store on the one hand contains an aerogel felt insulation characterized by a very low thermal conductivity of 0.013 W/(m∗K) to reduce the heat flux from the store to the interior. On the other hand microencapsulated phase change material (PCM) with a melting point of 23 °C is integrated into the double layer of gypsum plasterboards which are screwed on the metal profiles of the stud wall. By melting the PCM the room temperature can be kept more constant or at least temperature peaks of the room can be decreased, respectively. During night hours the PCM can regenerate by solidifying again.

The main frame of the prototype that is shown in Fig. 2 is made of aluminium profiles for stiffening the whole construction and for connecting the respective components to this metal frame. In Fig. 7 the substructure below the prototype is shown. This substructure does actually not belong to the façade element itself, but is necessary for an easy transportation of the prototype. For instance, the prototype has to be moved from the workshop to the dynamic solar simulator to determine its thermo-physical characteristics (see also chapter 5).

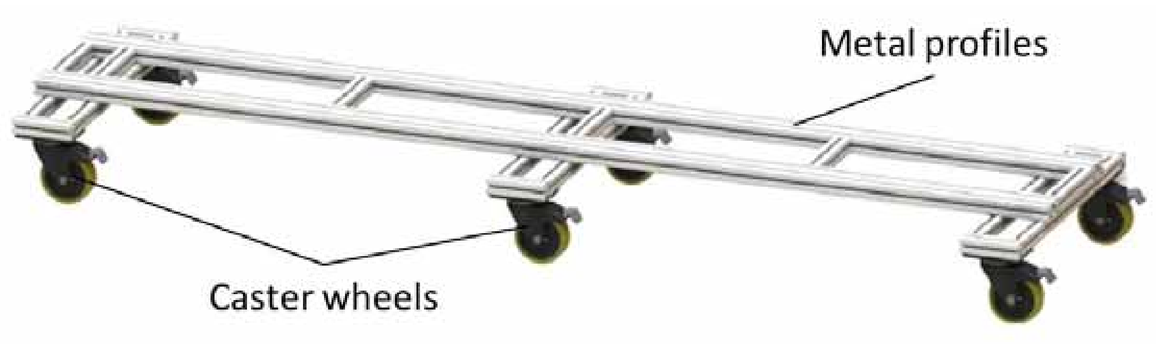

Fig. 7: Substructure for transportation of the prototype

The complete prototype has a length of around 2.5 m, a height of 2.0 m and a thickness of 0.4 m and it weighs about 600 kg with empty store and 1,000 kg in case of a store filled with water. Concerning the dimensions it must be said that this prototype for laboratory testing is actually larger than such a façade element would be when it is integrated into a real building. As will also be discussed in chapter 4 the thickness of 0.4 m complies with the dimension of a real building façade, however length and height of the façade element for a residential building are supposed to account for only about 1.0 m and 0.8 m, respectively. The reason for this scale-up of the prototype compared to the envisaged integration into a real building lies in the outdoor testing of the prototype: as will also be mentioned in chapter 5 the prototype is going to be integrated into a dwelling/office container and the TRNSYS simulations that were conducted for this container with such a façade-integrated solar thermal system show that a multifunctional façade area of only around 0.8 m² would be too small to achieve considerable solar fractions for such a case [3 - 5].

3.5. Prototype assembling

The first step of assembling the prototype was to build up the substructure with the caster wheels (cf. Fig. 7). After this the respective aluminium profiles were connected to each other and to the substructure to form the metal framing of the prototype. In a next step the plastic profiles for framing the slim sides of the hot water store were built up and connected to the metal framing of the prototype. Before integrating the store the rigid foam insulation panel and the aluminium sheet below were cut to their required shape and mounted to the substructure. Now the prefabricated store could be inserted into one of the slim sides of the prototype and pushed forward until it was positioned in the plastic framing profiles. After this the horizontal metal framing profiles at the front and back side of the store were mounted. On the one hand these profiles are connected with the plastic profiles at the slim sides by angle brackets (cf. Fig. 2), while on the other hand the corresponding profiles of the front and back side are joined to each other by a thread rod crossing the hot water store at the middle of the store. The next steps were the painting of the outside wall of the store with the absorber coating and the mounting of the vacuum insulation panels. After fixing various temperature sensors at the surface of the front and back side of the store, the transparent thermal insulation could be connected with the main frame according to the descriptions in chapter 3.2. Then the complete hydraulic system, consisting of the plate heat exchanger, the pump, the thermostatic mixing valve, pipes, temperature sensors and flow meters, was built up. The controller, the data acquisition system and the power supply are not part of the façade element itself and are therefore placed outside of the prototype. In a next-to-last step the metal stud wall was established which meant connecting the horizontal metal profiles at the top and bottom with the main frame of the prototype, inserting the vertical profiles into the horizontal ones, filling the gaps with the aerogel felt insulation and finally screwing the gypsum plasterboards with the microencapsulated PCM onto the metal profile construction. As can be seen in Fig. 3 the slim sides of the prototype are covered with panels. Therefor rigid foam panels with a thickness of 3 mm were planked onto these sides by using screws and the T-slot nuts of the framing aluminium profiles. In Figure 2 a door adjacent to the transparent thermal insulation is visible. This door serves for a better access to the hydraulic components when changes or maintenance should become necessary, but the door is not a part of the real façade element in a residential building or at least it would not be located at the outside. More details of the construction and assembly of the prototype including further pictures can be found in [5].

4. Building integration and application of the façade element

In Fig. 8 an example of the integration of the solar thermal façade element into the façade of a residential building is illustrated. The façade element is a non-bearing part of the building envelope and can be integrated into new buildings as well as during the refurbishment of an existing building. As already mentioned above, the façade element is integrated into a building without the substructure and without the door, because these two parts only serve for transportation and access to the hydraulic components, respectively, but they are not necessary in a real building envelope. Also it was mentioned that the prototype was built up at a larger scale than a façade element would be dimensioned in real application which is due to the envisaged outdoor testing. As is highlighted by red color in Fig. 8, the window sills are supposed to serve as the place of integration for the façade element. In a typical residential building the dimensions of a window sill account for about 1.0 m in length and 0.8 m in height.

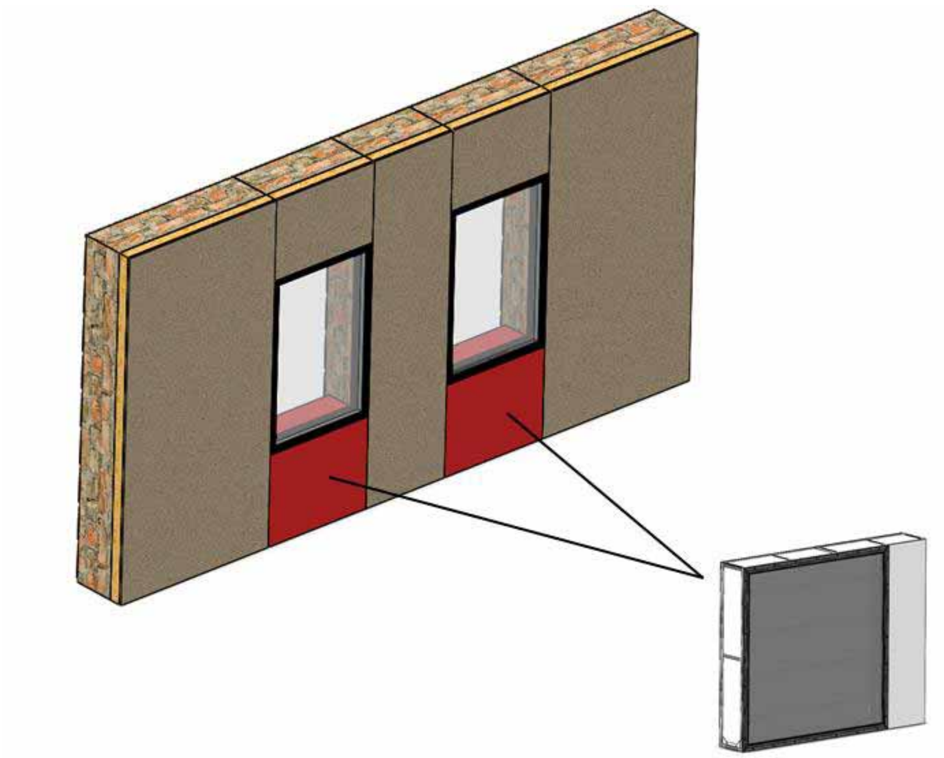

Fig. 8: Example for the integration of the solar thermal façade element into the façade of a residential building

The developed solar thermal façade elements are intended to be used as decentralized preheating units for the preparation of domestic hot water in larger multi-story residential buildings. This means that one or maybe also several of such façade elements per dwelling unit are integrated into the façade. Evidently, these façade elements can only partly cover the heat demand for domestic hot water preparation of a dwelling unit; for the exact figures dependent on various parameters see simulation results which are published in [3 - 5]. That is why the conventional domestic hot water and space heating system of the building will not be changed, but of course the façade element has to be hydraulically connected to the existing piping system. The details of the hydraulic integration of the solar thermal façade element depend among other issues on the specific layout of the dwelling units and their size and position in different types of multi-story residential buildings.

Concerning the visual appearance of the solar thermal façade element it must be said that still further work is necessary to adapt and improve the layout so that the targeted appealing building integration, i.e. the high architectural quality of the BIST system, will be achieved.

5. Envisaged laboratory and outdoor testing

The prototype whose construction was described above was also equipped with measurement instrumentation. On the one hand this includes various temperature sensors for monitoring the temperature of the hot water store and the temperatures in different parts of the façade element, while on the other hand the heat fluxes and energy quantities in the water circuits are determined with the help of mass flow and temperature sensors. The details of the measurement instrumentation are described in [1] and [5].

In a first step it has to be investigated to which extent the chosen construction for the direct charging of the hot water store via solar radiation passing the transparent thermal insulation is working. In order to check that issue the prototype can, due to its set-up on a substructure for transportation (cf. Fig. 7), easily be moved to the outside on a sunny day or it can be exposed to the artificial solar radiation in the dynamic solar simulator at the TZS/ITW. The measurement of the temperatures of the hot water store will then give information about the applicability of the concept of using the outside wall of the storage tank as the solar absorber and directly charging the store by solar thermal energy via a transparent thermal insulation.

In a next step the heat loss rate of the hot water store of the prototype will be determined based on EN 12977-3. Furthermore, the prototype is going to be tested as a complete solar thermal system based on the CSTG testing method according to ISO 9459-2 in the dynamic solar simulator at the TZS/ITW (CSTG: Solar Collector and System Testing Group) [6]. These measurements aim at determining more precisely the thermal behavior of the whole solar thermal system, for instance concerning charging and discharging of the hot water store. For this prototype construction with solar charging via the transparent thermal insulation it is of special interest to find out, how fast the water in the store is heated up dependent on the ambient conditions. Besides the determination of amounts of heat transferred into and supplied by the system, also temperatures at the store as well as in the different layers of the façade element will be measured in order to get an insight into the temperature distribution within the façade element. On the one hand this test serves as a basis for information about the behavior concerning overheating in times of high solar irradiation, while on the other hand it is also helpful to assess the thermal stress of the respective components during semi-real operation. After finishing the laboratory tests also outdoor testing is going to be performed by integrating the system into a dwelling/office container.

6. Conclusions

In this paper the development and construction of a prototype for a façade-integrated solar thermal system for the preparation of domestic hot water were presented and the envisaged form of building integration was discussed. The façade element is supposed to be integrated as a replacement of the window sill in above all multi-story residential buildings to serve for the decentralized solar preparation of domestic hot water for a dwelling unit. Furthermore, it was presented which laboratory and outdoor tests are going to be performed in the next months.

In a follow-up project, which can still be planned in detail, one or more of the developed façade elements are being further improved, especially with regard to mass production and they are going to be integrated into the façade of an adequate residential building in order to evaluate the performance of the multifunctional façade element under real operating conditions over a longer period of time. For this project we are still looking for interested industry partners, e.g. from the fields of architecture, building design, façade or window manufacturing, etc. who want to engage technologically and financially in this innovative and promising technological approach. Furthermore, we are also looking for suitable residential buildings for the façade integration of our newly developed multifunctional solar thermal façade-integrated system for domestic hot water preparation.

7. Acknowledgements

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