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Abstract. Wall and roof components made of steel sandwich elements are firmly established in industrial and commercial construction. They are cost-effective and characterized by excellent physical properties. Here, hybrid approaches from heating- and cooling ceiling construction were examined for the solar thermal activation of sandwich elements. Besides the implementation of the solar components, the connection to and the optimization of the system technology was focused. In addition, alternative piping materials were investigated numerically and experimentally. The performance as well as the static and thermo-hydraulic behavior of the new active components were simulatively and experimentally examined, and the economic viability of the variants was also checked. With the newly developed solar sandwich elements, an overall energy concept was developed with connection variants to the building services system, control and storage technology. Steel sandwich elements with mineral fiber core are well suited for the hidden integration of component parts such as pipe registers and heat conducting plates. The functionality of the component has been proven, the implementation of heat exchanger leads to considerable heat gains. In combination with a brine-to-water heat pump system, the solar panel can provide for a more sustainable operation and a significant size reduction of the geothermal source.

1. Introduction

The Federal Government's goals for climate protection policy are defined. The main focus is on reducing primary energy consumption from 20 % in 2020, by 30 % in 2030 and to 50 % in 2050 compared to 2008. Improvements in CO_2 reduction should be achieved in the building sector. For this reason, new, future-oriented solutions in construction are required to make buildings largely independent of fossil fuels [9]. The 200 million m² steel sandwich elements used in industrial and commercial construction [6] can contribute to increasing energy efficiency and can be used to use renewable energies. Requirements for energy efficiency and sustainability are increasing steadily and are being intensified by legal guidelines. In addition, new buildings will have to meet the lowest energy standards in the future. To implement this, the use of renewable and regenerative energies for power generation, heating, cooling and domestic water heating is to be standardized. So far, energy losses have generally been compensated for by greater component thicknesses. Steel sandwich elements with a mineral fiber core achieve a U-value of 0.31 W/m²K (d = 140 mm). The elements with a thickness of 300 mm predominantly installed in the Scandinavian area achieve a U-value of 0.139 W/m²K [1]. The aim of the research project is to use solar gains to reduce heating energy in order to save CO_2. In addition, the insulation thickness is to be reduced in perspective through the energy gained from the facade surface, and savings in building system technology should be possible.

Main focus in the current project was the conception and creation of solar-thermal-activated steel sandwich elements in order to check the practical implementation. This included the constructive development of the line training (e.g. harp, meander, alternative materials, cross-sectional shapes) and the implementation of the absorber components. For this purpose, the structural fixation on the cover plate and the connection to the system technology could be solved. The aim was to implement both technical and constructive measures in the context of the architecturally high-quality design. The creation of test specimens and their examination via a universal testing machine were also part of the investigations. Thus, experimental static tests (cf. section 3) and questions regarding the practical implementation could be verified equally.

The Institute for Solar Energy Research in Hamelin conducts research in the field of solar thermal in combination with various usage and storage scenarios. The main focus of the presented research work was to carry out FEM simulations as well as practical tests on indoor and outdoor test benches under real weather conditions to investigate the performance of the solar-thermal-activated steel sandwich element variants. The same was true for the computational and experimental evaluation of the correspondent solar assisted heat supply systems. The final result was the comparison of the developed plant concepts in relation to the selected application scenarios and their evaluation in the form of an economic and ecological balance.

2. Concept of thermal component activation

In the preliminary project, the installation of heat exchangers in steel sandwich elements with a polyurethane foam core was examined for the first time [3]. Here the first positive results for thermal activation could be worked out. The effort for the implementation of the pipelines in the industrial context was assessed disadvantageously with regard to the continuous PUR sandwich production. In the research project presented here, energy-generating technologies were implemented in steel sandwich elements with mineral fiber core [5]. In direct comparison to polyurethane foam, the mineral insulation core has positive properties: high fire resistance, high thermal and acoustic insulation. The solution developed is based on a hidden integration of solar thermal component parts. The resulting solar activated panels in lightweight steel construction for industry and commercial construction hereby take into account the primary and decisive economic concerns of the construction. For this purpose, constructive solutions from the climate ceiling area were tested and adapted. In addition, implementation scenarios for continuous and discontinuous production variants were shown.

2.1 Manufacturing the demonstrators

In the research project presented, energetically activated sandwich elements with mineral fiber core with a thickness of 150 mm were developed. The demonstrators were manufactured at the Dortmund University of Applied Sciences and with the help of the cooperation partner from the area of climate ceilings (Company Schmöle, Menden).

Figure 1: Demonstrator with a meander and 24 heat transfer plates, pipe distance 102 mm

Sandwich element data for demonstrators (cf. Figure 1)

- Dimension of the steel sandwich element 1200 mm x 2000 mm, thickness 150 mm
- External cover plate = micro-profiled, internal cover plate = lined
- Mineral fiber core: non-flammable (fire protection class A1), density 100 kg/m³
- U-value: 0.27 - 0.29 W/m²K (for 160 mm thick sandwich element with approval and Ü-mark)
- Spans up to 7 m [1]
- Outer flat steel cover plate (t = 0 60 mm): coating PVDF 65 µm (outside), 10 µm polyester resin (inside) [8]
- RAL 7012 absorption α =0,865 emmisity ε= 0,950

For the implementation, the micro-lined steel cover plate of the sandwich element was removed mechanically. The outer mineral fiber surface was occasionally damaged by the separation process. The flaws mentioned were subsequently corrected with a PU-adhesive when fixing the new, flat cover plate. The corresponding meander geometry was milled into the mineral fiber blocks using a router. The solar components were then covered and placed flush in the sandwich element. Meander registers offer good thermal performance as well as a seamless tube design that ensures continuous contact with the outer cover plate. Joining points such as sockets or fittings are not necessary with this design. The meander was realized with the help of the cooperation partner and the forming was carried out using a bending table. In the subsequent process, the entire meander tube register is given the flattened D tube cross section. Finally, the heat exchanger consisting of heat transfer plate and meandering register is applied to the steel cover plate. A 1-component PU adhesive used for the continuous production was used to glue the cover. Potential raw materials for demonstrator construction, such as copper and stainless steel, were selected on the basis of previous the investigations with small-format samples (cf. Table 1).

Table 1: Variants of the demonstrators

variant	pipe material / line variant	geometry	heat transfer plate
1	Cu-meander, Ø =12 mm, t =0.35 mm	D-Rohr	alu, t = 0.5 mm, acrylate tape
2	Cu-meander, Ø 12 mm, t = 0.35 mm	D-Rohr	steel, t = 0.32 mm, acrylate tape
3	stainless steel-meander, Ø =10 mm, t = 1.0 mm	D-Rohr	steel, t = 0.32 mm, acrylate tape
4	Cu-meander, Ø = 12 mm, t = 0.35 mm	D-Rohr	alu, t = 0.5 mm, pu-adhesive

2.2 Constructional implementation

As part of the project, various connection variants of the raw registers to the manifold for module interconnection were developed. A 90° connection was chosen for the demonstrators. The pipe ends are led from the sandwich module into the interior of the building at a 90° angle. The laying of the sandwich elements, the meandering register is aligned horizontally. The advantages of this variant are better accessibility and inspectability of the manifolds. Horizontal and vertical laying of the sandwich modules is also possible. For the passage of the pipe ends into the interior of the building, perforations in the inner cover of the sandwich element are necessary. A diffusion-tight sleeve at the penetration points was developed to prevent the penetration of water vapor and manufactured using 3D printing [4].

3. Static behavior

On the basis of series of tests, it was demonstrated that the implementation of the absorber technology (heat transfer plate and male tube registers) leads to a static upgrading of the steel sandwich element.

The test specimens of measurements were identical to the structure of the demonstrators, but are only one part cut-out (length 500 mm; width 102 mm; height 150 mm). All test specimens from test 1-4 were manufactured under the same conditions. A sample specimen (test 1, reference sandwich module) without absorber technology was used to compare the measured values. Furthermore, a cut-out of an industrial sandwich module was tested (test 0). The profiled steel cover plate contributes to the increase of the value of 54 % compared to the reference sandwich module with flat steel cover plate. The measurement series in Table 3 shows that the static properties of the sandwich element with integrated solar thermal energy improve up to 146 %. As well as from the first series of measurements, it can be inferred from the values that the heat transfer plate made of tinned steel have a higher stiffness than that of aluminium. For experiments 3 and 4, the difference is 40 %.

Table 2: Measurement series 2: Results of the 3-point bending tests with mineral fiber core.

attempt	geometry, pipe, material, dimension	tinned steel heat transfer plate (t = 0.32 mm) [%]	tinned steel heat transfer plate (t = 0.32 mm) [N]	aluminum heat transfer plate (t = 0.5 mm) [%]	aluminum heat transfer plate (t = 0.5 mm) [N]
0	Industrial sandwichmodule (without pipe and heat transfer plate)	154 %		966 N	
1	Referenece sandwichmodule 1K PU (without pipe and heat transfer plate)	100 %		628 N	
2	D-pipe stainless steel (Ø = 10 mm, t = 1.00 mm)	189	1186	178	1117
3	D-pipe copper (Ø = 12 mm, t = 0.4 mm)	211	1324	171	1076
4	D-pipe steel, outside galvanised (Ø = 12 mm, t = 1.2 mm)	246	1546	206	1295

4. Energetic evaluation of demonstrators

The performance of the manufactured demonstrators (cf. section 2.1) was assessed by the research partner ISFH in accordance with ISO 9806 for the characterization of solar thermal collectors [7]. These investigations were carried out in the institute's own solar simulator under laboratory conditions (indoor) as well as in an outdoor test rig under real weather conditions (location Hamelin).

4.1 Indoor measurments / outdoor measurments

For the indoor measurement, an irradiation of 880 W/m^2 and ambient temperature of approx. 26 °C was set. A previous simulation study based on Finite-Element-Method (FEM) was used to determine the theoretical zero-loss-efficiency η_0 achievable under ideal conditions. η_0 represents the maximum thermal efficiency of the collector and correspondents to the fraction of incident solar radiation which is transferred to the fluid if the fluid temperature equals the ambient air temperature. For the defined panel color we reported a value of 0.74, which is much lower than the experimental results shown in Table 3 [2]. This can be well explained by the approximately 30 % inactive area on the real demonstrators. This edge area, which is not thermally activated, is used to fix the element to the frame construction. The measured values of the demonstrators are very different, depending on the specific design. The higher efficiency is achieved with heat transfer plates and pipes made of aluminum, which exhibits a higher thermal conductivity than steel. As expected, the material chosen has a much stronger impact on the pipes than on the heat transfer plates, so that steel represents an interesting alternative to aluminum for the use with these components. Beside the different design, the manufacturing quality also affects the results, as confirmed by a thermographic examination of the demonstrators' cover, used to document the homogeneity of the temperature distribution induced by the heat exchanger. Especially the thermal imaging of variant 1 and 3 reveals a nonuniform contacting of the pipe register and the heat transfer plates to the steel cover plate of the sandwich panel. This negatively affects the heat transfer mechanisms and thus the thermal performance of the two variants (ca. 3-4%).

Table 3: Zero-loss effciency of demonstrators from indoor-measurement [2]

demonstrator no.	heat exchanger design	Zero-loss thermal efficiency
1	copper-meander, D-pipe, steel-heat transfer plate	$\eta_0 = 0.523$
2	copper-meander, D-pipe, aluminum-heat transfer plate	$\eta_0 = 0.533$
3	stainless steel meander, D-pipe, steel heat transfer plate	$\eta_0 = 0.456$
4	copper-meander, D-pipe, aluminum-heat transfer plate	$\eta_0 = 0.563$

In order to obtain more reliable information about the performance of the panel under real conditions in addition to the results of the indoor measurements, selected demonstrators (variants 2 and 4) were also measured outdoor. The comparison of the zero-loss efficiency η_0 shows a negligible difference between indoor and outdoor measurements, amounting to 1 % for variant 1and 0.7% for variant 4.

5. Dynamic building simulation with component-activated facade element

On the basis of a dynamic building simulation with the software TRNSYS, an energetic evaluation of the sandwich panels implemented in a solar assisted heat supply system of a sample non-residential building with an area of 900 m^2 was carried out. The characteristic values of the solar sandwich elements used for this purpose are in accordance with the results of the thermal efficiency measurement. For the simulation, a south oriented facade area of 60 m^2 and 120 m^2 was activated, which represent 17% and 33% of the total area respectively. Two heat pump systems (Figure 2) were compared: 1. Brine-to-water heat pump system – here a borehole heat exchanger is the heat source of the heat pump, 2. Air-to-water heat pump system - the ambient air serves as a heat source of the heat pump. For the brine-to-water heat pump the impact of solar regeneration of the geothermal resource by the solar sandwich panels was analyzed (Figure 2, left). The heat distributed to the building interior via a low-temperature floor heating system.

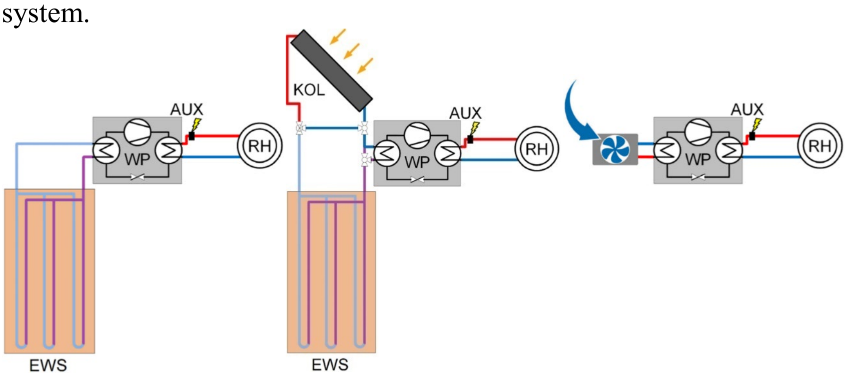

Figure 2: Investigated system configurations. Reference: brine-to-water heat pump system with borehole heat exchanger without solar thermal regeneration (left), 1. Variant with solar thermal regeneration (middle), 2. Variant with an air-to-water heat pump system (right)

The heat pump system with borehole heat exchangers and without solar regeneration (Figure 3, left) is assumed as reference. The results of the simulation show that a 120 m^2 component activated facade area can slightly improve the system performance (+5%) but significantly reduce the length of the geothermal probes by 25% to 30% or even the overall size of the area necessary for the borehole field by up to 80%, thus reducing the investment costs and extending the installation potential. Furthermore, by the use of the solar thermally activated sandwich elements in combination with this kind of heat pump system, the long-term cooling of the soil in which the geothermal probes are located can be compensated and the system can be operated in a much more sustainable way. In contrast to a non-regenerated system after a few years of operation, the soil temperature reaches a constant value (Figure 3). Simulations with an air-to-water heat pump system (Figure 3, right) confirm that this solution has a significant lower efficiency (-35%), which results in a correspondently higher power consumption.

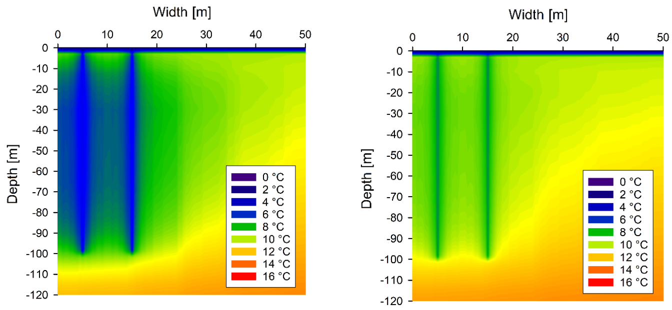

Figure 3: Comparison of soil temperature distribution next to the borehole heat exchangers without solar regeneration (left) and with solar regeneration (120 m² collector area, right) after 25 years operation

6. Conclusions

The research project investigated the integration of solar thermal components into steel sandwich elements with mineral wool fiber core for industrial and commercial buildings. The solar panel development of followed the principles of economic efficiency. The solar components (heat transfer plate and meander register with a D-shaped cross section) were selected in order to increase the contact surface to the outer steel deck sheet and thus the energy efficiency of the panel. The constructive feasibility of integrated solar thermal components in steel sandwich elements could be demonstrated. In order to guarantee an economic implementation, the industrial production of these panels is indispensable. For this purpose, scenarios for the integration of the heat exchanger in the discontinuous and continuous manufacturing process of sandwich elements were investigated and evaluated. Simulations of heat supply systems for an exemplary commercial building show that solar activated sandwich panels can be used to regenerate high-efficiency brine-to-water heat pump systems, thus ensuring a sustainable operation and significantly reducing the size of the geothermal source. Other promising system configurations (e.g. combination with ice storage) or applications (e.g. cooling) are subject of current research work. Another advantage: The solar thermal system is concealed integrated into the building envelope and thus speaks for an attractive architectural quality. Summing up, the paper shows that the goal of counteracting the energy loss of the building with an active measure is a sensible alternative to increasing insulation thickness.

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