# First experimental investigations of a facade-integrated adsorption system for solar cooling

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### Abstract

In this work, a novel facade-integrated adsorption system for solar cooling is investigated experimentally with a first prototype. This system consists of an evaporator, which is installed as cooling ceiling, a condenser and an adsorber. To precisely measure the achieved cooling power rates, the system is tested with an almost adiabatic test chamber, which is placed in an air-conditioned laboratory, and the evaporator is installed as cooling ceiling into the chamber. The adsorber are designed as panel-shaped elements and are mounted in standard facade frames on load cells in the laboratory. The adsorber is regenerated by an infrared heater. The first experimental tests reveal minimum evaporator temperatures of around 6 °C and the outer bottom of the evaporator can be maintained below 10 °C for over 15 hours.

*Keywords: Solar Energy, Thermal Energy Storage, Adsorption Chiller, Cooling Ceiling, Building Energy Systems*

## 1. Introduction

Due to its high demand for resources and energy, the building sector accounts for almost 40% of the global carbon dioxide emissions (United Nations Environment Programme 2020). Therefore, in order to achieve the ambitious climate protection goals, it is essential to reduce the required amount of building material in the construction of future buildings as well as to operate these lightweight buildings more energy efficiently or, if possible, energy self-sufficiently. Against this background, a novel, facade-integrated adsorption system for solar cooling of lightweight buildings is being developed within the Collaborative Research Centre 1244 at the University of Stuttgart. The proposed adsorption system combines the functionality of energy storage and cold production, with minimum occupation of inner building space. After detailed simulations of a reference case confirmed the general functionality of the proposed cooling system (Boeckmann et al. 2024), a first prototype was setup in an air-conditioned laboratory. This work introduces the prototype set-up and presents first measurement results.

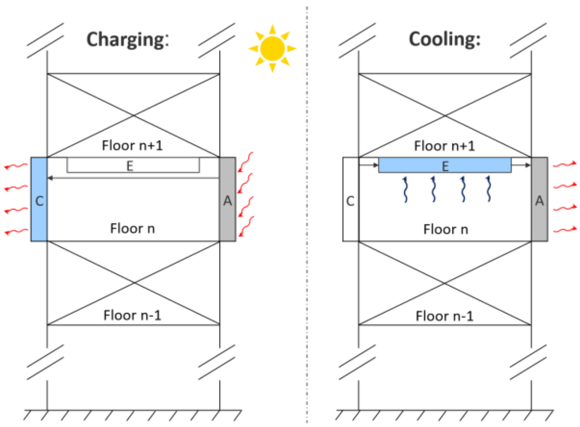


**Figure 1: Cross-section view and operating principle of a high-rise building equipped in floor n (exemplarily) with the facade-integrated adsorption system for solar cooling. The main components are: A-adsorber, C-condenser, E-evaporator. The regeneration phase, in which the reactor is heated up by solar irradiation, is shown on the left-hand side and the cooling phase on the right-hand side. The colored arrows indicate the main heat fluxes during the two phases. (Boeckmann et al. 2024)**

Adsorption-based cooling is a highly researched cooling technology (Chauhan et al. 2022) and current experimental research addresses the heat transfer design of the adsorber (Wang et al. 2022), the applied working pairs (Allouhi et al. 2015; Cabeza et al. 2017), the influence of thermal operation conditions (Liang et al. 2023) as well as the operation


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under real conditions (Bujok et al. 2022; Mat Wajid et al. 2021). However, the work of (Hallström et al. 2014) is the only work know to the authors in which the solar thermal collector and the adsorber are integrated into one component. This element was not designed for the integration into the facade and cooling could only be produced during the night.

The adsorption system consists of the three components adsorber, condenser and evaporator, refer to **Figure *1***. The adsorber and the condenser are integrated as panel-shaped elements into the building facade. The particular challenge lies in the efficient absorption of solar irradiation by the adsorber during the regeneration phase and the sufficiently high heat release to the ambient during cooling operation. The evaporator is installed as a cooling ceiling in the building. For cooling, the evaporator is connected to the previously regenerated adsorber, whereby the cooling power can be controlled by throttling the vapor mass flow.

This work aims to provide a detailed description of the developed experimental setup, including detailed descriptions of the three main components adsorber, condenser and evaporator as well as the installed sensors, the introduction of the test chamber, in which the system is tested and the heating system to regenerate the adsorber. The prototype is designed based on the previous simulation studies partially presented in (Boeckmann et al. 2024). Finally, the successful installation is demonstrated through first cooling operations with the system.

The paper is organized as follows: In Section 2, the experimental setup is introduced and the experimental procedure is presented in Section 3. The experimental results are shown and discussed in Section 4 and finally, the study is concluded in Section 5.

## 2. Experimental setup

### 2.1 Adsorber

The adsorber is panel-shaped with dimensions of 890 mm height, 1100 mm width and 87 mm depth. The design scheme of the adsorber is given in Figure 11. It is enclosed by a metal casing at the back as well as the sides and by a metal absorber sheet at the outer face and is vertically attached to a facade of the building or to a wall in this experimental setup, respectively. To ensure mechanical stability, which is one of the main challenges with flat-shaped low-pressure constructions, metallic pins are used as known from evacuated solar thermal collector, refer to Figure 2 (left). These add only little mass and thermal bridges. The adsorber is filled with the granular adsorbent zeolite 13X, while a mesh separates the adsorbent from an adjacent vacuum gap, see Figure 2 (right). This allows for a good distribution of the vapor inside the adsorber. The adsorber is thermally well insulated towards the building's envelope by 20 mm vacuum insulation panels on the back and the sides of the casing. Three ISO-KF16 in-/outlets for the water vapor are integrated into the back of the adsorber with the central one being used in the studies of this work. Metal fins are integrated into the zeolite packed bed to overcome the heat transport limitations of the adsorbent.

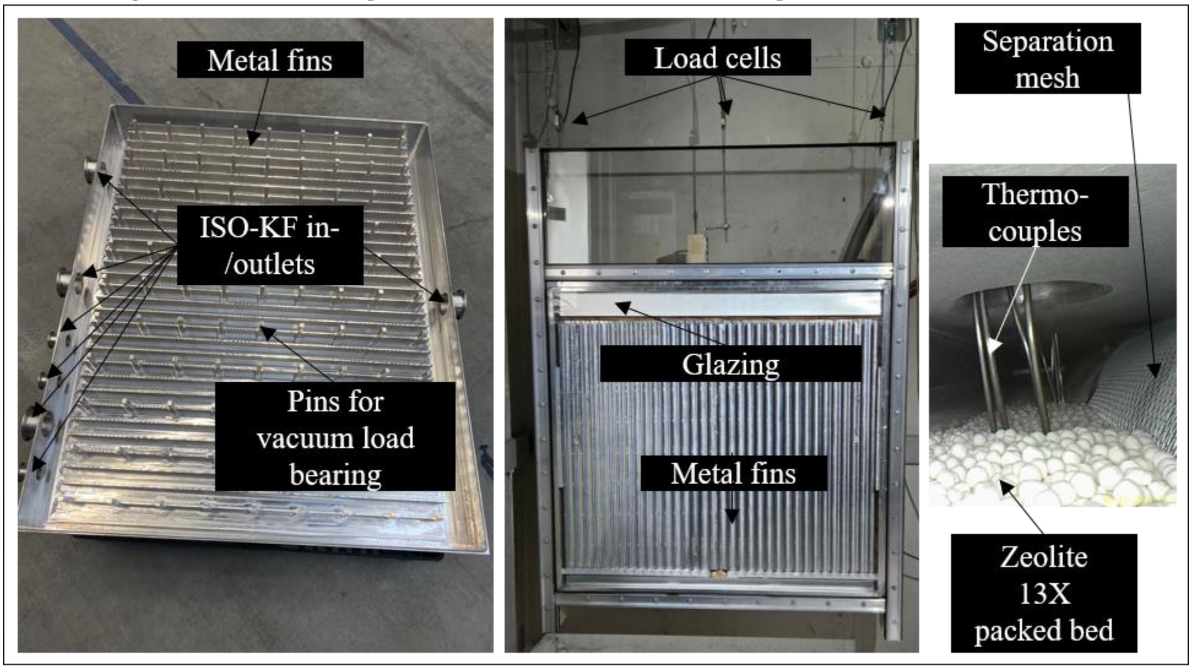


**Figure 2: Photo documentation of the adsorber. Left: The inside of the adsorber during the manufacturing. The metal fins, which are integrated into the zeolite packed bed, and the pins for vacuum load bearing are visible. Middle: The adsorber installed into the facade frame and mounted on loads cells in the laboratory. Right: Insight into the filled adsorber with a borescope.**

In order to efficiently absorb the solar irradiation during the regeneration phase, the outer adsorber surface face is covered by a metal absorber sheet as well as a low iron float glass, with a Ug-Value of 5,8 W/m²K and a g-Value of 91 %, shown in Figure 2 (middle). Between the absorber sheet and the glazing, there is an air channel, which is closed by a flap during the regeneration phase, while it is open during the cooling phase to efficiently transfer the released heat of adsorption to the ambient by free air convection through the air gap channel (Greiner et al. 2022). To enhance the heat release in the cooling phase, the absorber sheet is equipped with vertical metal fins in the air gap to increase the heat transfer surface. This structure was simulation-based analyzed in (Greiner et al., 2022) and supplemented with variant studies.

On the top of the adsorber, three ISO-KF25 inlets allow for the vacuum tight feed through of thermocouple sensors into the zeolite packed bed. Further three ISO-KF 50 inlets at the top as well as one ISO-KF 50 inlet at the bottom allow to fill/release the adsorbent into/from the adsorber.

The adsorber is integrated into a standard facade construction in order to test the components properties under nearly building conditions and to demonstrate the possibility of integration. This is the Stabalux AK-H system, a mullion-transom construction made of laminated timber with an aluminum attachment.

## 2.2 Condenser

The condenser is panel-shaped and has the same dimensions as the adsorber (890 mm height, 1100 mm width and 87 mm depth). The design scheme of the condenser is shown in Figure 12. Similar to the adsorber, the condenser is enclosed by a metal casing and is attached vertically to the facade of the building or to the outer wall of the test chamber in this experimental setup, respectively, see Figure 3 (left). Internal metal fins are included to enhance heat transport to the ambient, and thus, improve the condensation rate. Furthermore, theses fins ensure mechanical stability. The backside of the condenser is thermally insulated by 20 mm vacuum insulation panels. In the regeneration phase, vapor flows from the adsorber into the condenser and condenses on the metal fins or the water surface, releasing the heat of condensation to the fins or the water, respectively. The heat is then conducted through the internal fins to the external fins, where it is emitted to the ambient air. Furthermore, the water phase is in direct contact to the outer wall and heat is being transferred to the ambient through the outer wall.

Similar to the adsorber, the condenser is installed into the same facade construction.

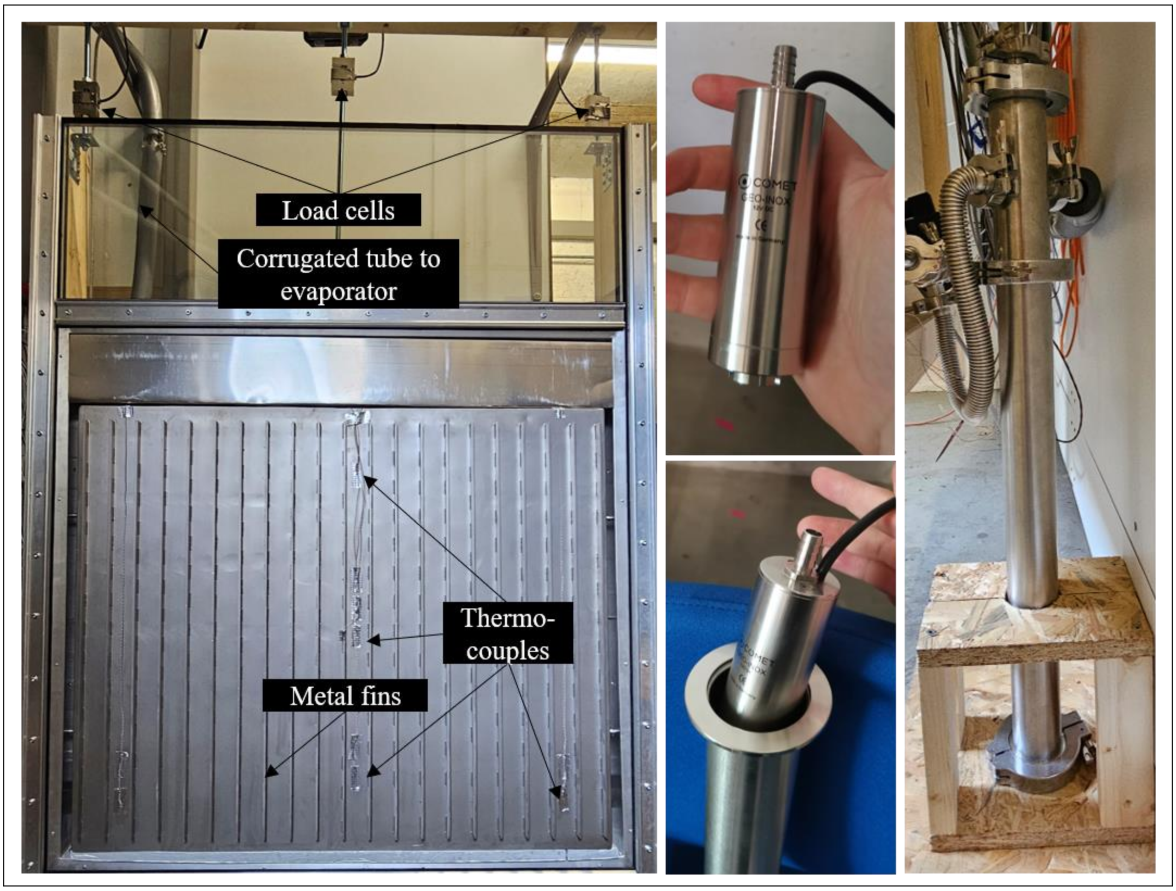


**Figure 3: Left: Photo documentation of the condenser installed into the facade frame mounted on load cells in the laboratory. Middle and right: Vacuum-tight pump realized by installing a submersible pump into vacuum tubes.**

## 2.3 Evaporator

The quadratic evaporator with a side length of 1000 mm and a height of 67 mm is also enclosed by a metal casing. It is installed as a cooling ceiling inside the building or into the test chamber in this experimental study, refer to Figure 4 (left). The applied box-shaped configuration is a very simple configuration, chosen in this work to determine the potential of the system with respect to the cooling rate. Nevertheless, more complex solutions such as pipe coils or active ventilation are possible and could be investigated in the future works. Vapor is extracted from the evaporator by the adsorption in the adsorber during the cooling phase, which reduces the pressure in the evaporator. Thus, evaporation is induced and the remaining water is cooled due to extracted heat of evaporation. The water then cools the metallic bottom sheet of the evaporator, which is in direct contact with the air inside the room.
In Figure 4 (right) the top of the evaporator with the sensors as well as the ISO-KF16 in-/outlets can be seen.


**Figure 4: Photo documentation of the evaporator. Left: The evaporator installed as cooling ceiling into the test chamber. Right: View on the top of the evaporator with sensors.**

## 2.4 Couplings

The components are connected with vacuum-tight corrugated tubes, which offer a certain flexibility. Valves are installed to open and close the connections between the components and a controllable throttle is used between evaporator and adsorber to control the inlet pressure of the adsorber, which allows to set the adsorption rate and thus the evaporation rate. This allows to control the evaporator temperature. An overview of all connections and valves is given in the hydraulic diagram in Figure 5.
The condensed water is pumped from the condenser to the evaporator using a vacuum tight pump, see Figure ***3*** (middle and right). This is realized by integrating a 12 V submersible pump into a 50 mm ISO-KF50 tube and feed a 10 mm hose through a corrugated tube into the evaporator. The electrical connection of the pump is enabled by vacuum tight electrical feed through.

## 2.5 Sensors

Three variables are measured for the components: Temperature, pressure and weight. The latter is measured via load cells and allows to calculate the water vapor flow between the components. Furthermore, current water uptake of the adsorber can be estimated by the weight measurements. For the temperature, thermocouple sensors are fed into the vacuum components via special feedthroughs and a reduced measuring grid is used. For all components the temperature distribution over the height is measured at four points. For both evaporator and condenser these points cover water as well as vapor phase. Additionally, for the adsorber the temperature distribution in width and depth between the fins is measured with four sensors each. The pressure is measured at the vapor inlet of all components as well as at one additional position for condenser and evaporator. In order to measure the vapor distribution inside the vacuum gap of the adsorber, two additional pressure sensors are installed over the height. Furthermore, all outer surfaces are equipped with thermocouples. An overview of all installed pressure sensors as well as thermocouples inside the components is shown in Figure 5.
An automation station with a programmable logic controller (PLC) is used for logging measurements, control, regulation and model identification of the system.

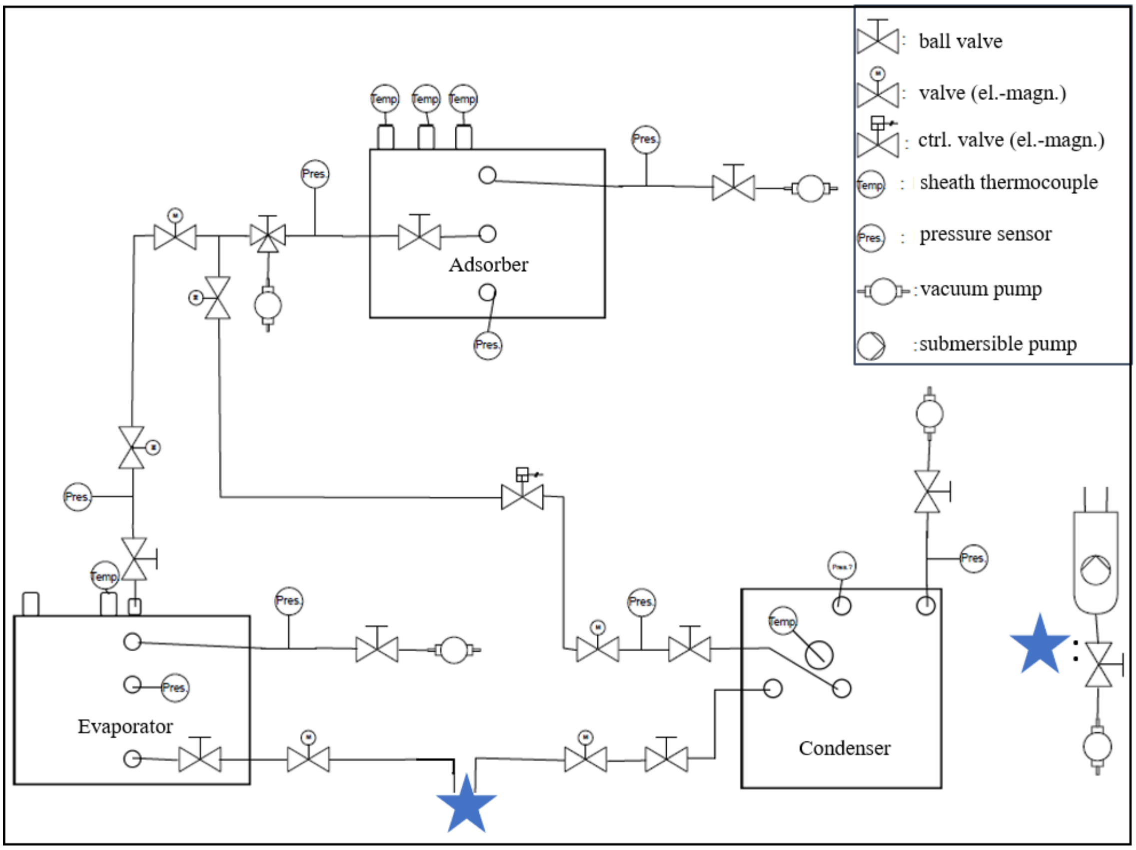


**Figure 5: Left: Hydraulic diagram of the adsorption cooling system.**

## 2.6 Test chamber

The adsorption cooling system is tested in a chamber with a multi-layer insulation concept, in which the evaporator is placed, refer to Figure 6. The wall structure consists (from outside to inside) of a layer of 8 mm thick High Pressure Laminate (HPL), 100 mm mineral wool, 18 mm oriented strand board (OSB), 20 mm vacuum insulation panel and 12 mm multiplex board. Each boundary layer temperature between the wall layers is recorded by two thermocouples. This resolves the heat dissipation through the side walls and the ceiling element. To measure the cooling capacity of the evaporator, the insulated room is brought to a constant temperature by supplying a continuously adjustable heating power. The room temperature is measured with a network of 12 measuring points at different heights and surface points using precise resistance thermometers. The heating power is delivered to the room air by an electric heating system. To identify the actual heat input into the test chamber, the electrical power provided to the heating system is measured. Homogeneous room air is achieved by a uniform flow provided by a controllable fan.

## 2.7 Heating system for regeneration

The adsorption system is regenerated by heating up the adsorber to desorb water vapor from the zeolite packed bed. In the laboratory setup this is done by an infrared heating system, which consists of heating wires in a thermally insulated construction, see Figure 7. The inside of the heating system fits perfectly the outer dimensions of the adsorber to reduce heat losses. The heating wires are resistance wires of the material kanthal 1.4765 with a diameter of 1.5 mm and a specific resistance of 0.7745 Ω/m. A total length of 34 m is used to reach thermal power rates up to 2000 W with a maximum voltage of 230 V possible. A voltage controller allows for continuous setting of the required thermal power.

**Figure 6: Pictures of the thermally high insulated test chamber. Left: Outside of the chamber with 100 mm mineral wool. Middle: 20 mm vacuum insulation panels installed to the inside of the chamber. Right: Inner top layer of 12 mm multiplex board.**

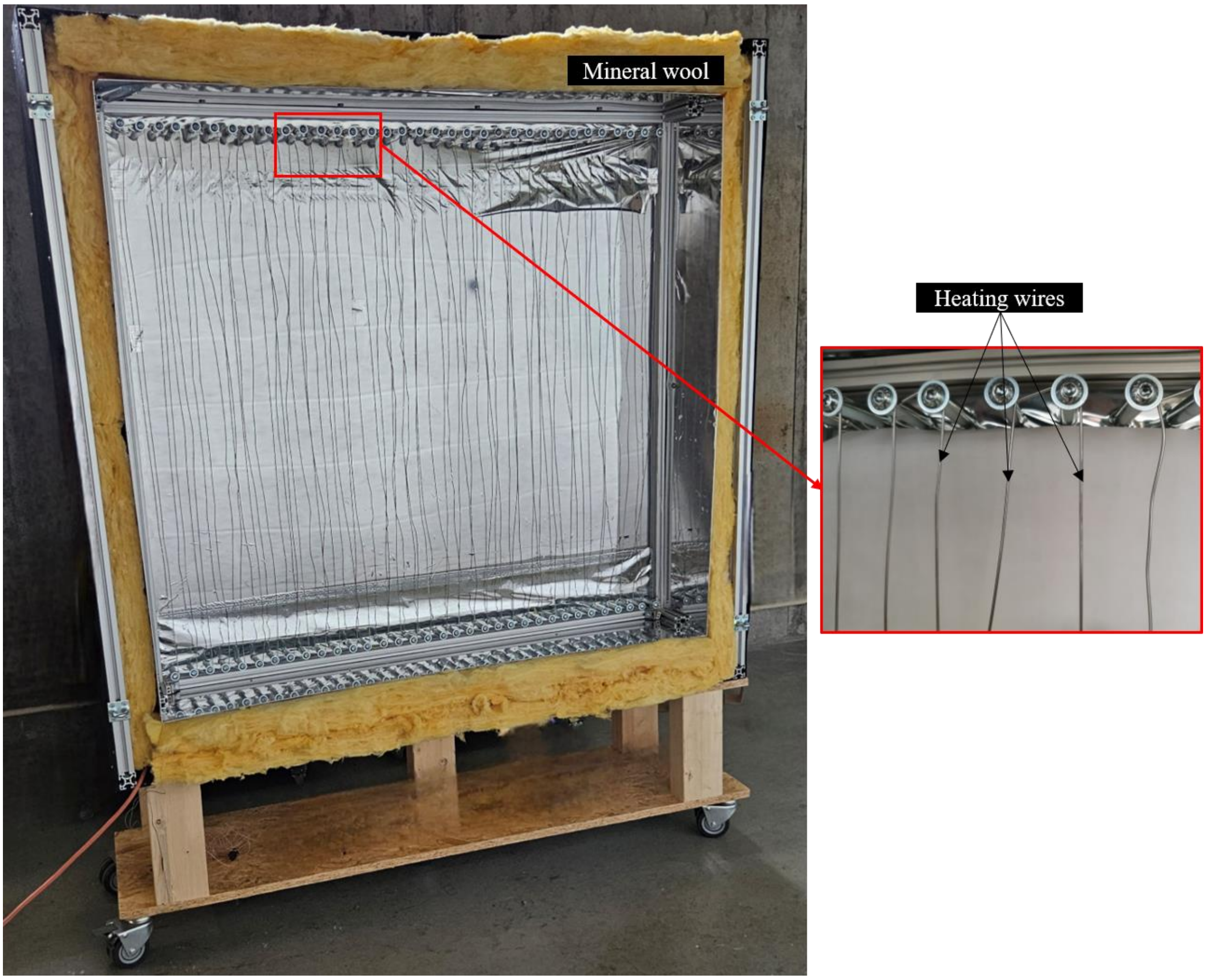


**Figure 7: Pictures of the heating system for the regeneration of the adsorber. Left: Full heating system with insulation. Right: Detail of the heating wires.**

# 3. Experimental procedure

## 3.1 Initial leak test

The three components adsorber, condenser, evaporator are evacuated after installation into the laboratory setup and leak tests are performed for more than 60 h to check if no leaks raised during the transport of the components or the installation. This further ensures that the system is vacuum tight and minimizes the risks for issues due to inert gases in the low-pressure system during the operation.

## 3.2 Cooling tests

The first cooling tests are performed after commissioning of the system with the new adsorbent zeolite 13X. For this reason, the water uptake levels are lower as in the later operation. Nevertheless, these tests allow to test the system under ideal regeneration conditions.
The cooling tests start with the connection of the adsorber and the evaporator, which immediately induces both adsorption of vapor and thus, evaporation in the evaporator. To investigate the full potential of the adsorption system, the temperature control of the evaporator is not applied. The temperatures of the vapor and water inside the evaporator as well as the temperature distribution in the test chamber are measured.

# 4. Results and discussion

## 4.1 Initial leak test

The results of the initial leak test can be seen in Figure 8. For each component the data of two pressure sensors are evaluated. It is found that all components are free of any leaks as there are no significant pressure increases over time. The pressure levels inside the evaporator and condenser are almost constant since they are tested empty and the small differences between the two sensors are within the measurement inaccuracies.
The leak test of the adsorber is done after it was filled with zeolite 13X and before the final complete evacuation. Thus, some gas molecules were still inside, which explains the slightly higher pressure levels compared to the condenser and evaporator as well as the higher fluctuations due to ad-/desorption processes. Nevertheless, it is clearly found that the adsorber is vacuum-tight and the differences between the two pressure sensors are within the measurement inaccuracies.

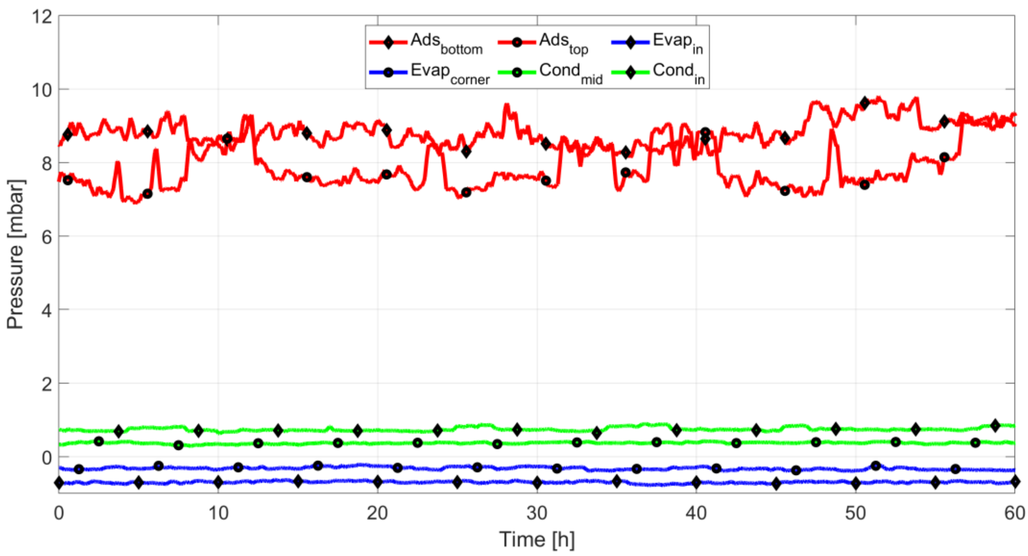


**Figure 8: Evolution of the pressures inside the three components adsorber (red), condenser (green) and evaporator (blue) over time during the initial leak tests.**

## 4.2 Cooling tests

Three cooling tests are performed during the commissioning of the novel developed facade integrated adsorption system for solar cooling. The first two tests take only around 1.5 hours, while the third test was performed over 24 hours. The results of the last test are shown in Figure , where the blue curve is the temperature at the central outer bottom of the evaporator and red as well as the green curves are the measurement data of the four sheath thermocouples that are fed into the evaporator.
It is found that a minimal temperature of around 6 °C was reached inside the evaporator. The bottom of the evaporator, which is in contact with the room to be cooled, is cooled down to below 9 °C and this a temperature

below 10 °C can be maintained for more than 15 h. Furthermore, a stable stratification of the water temperature can be seen with the minimum temperature close to the bottom and the highest temperature at the top. This is favorable since the vapor pressure inside the evaporator is mainly influenced by the temperature at the top of the water phase. High pressure levels increase the adsorption rate and thus lead to a higher evaporation.

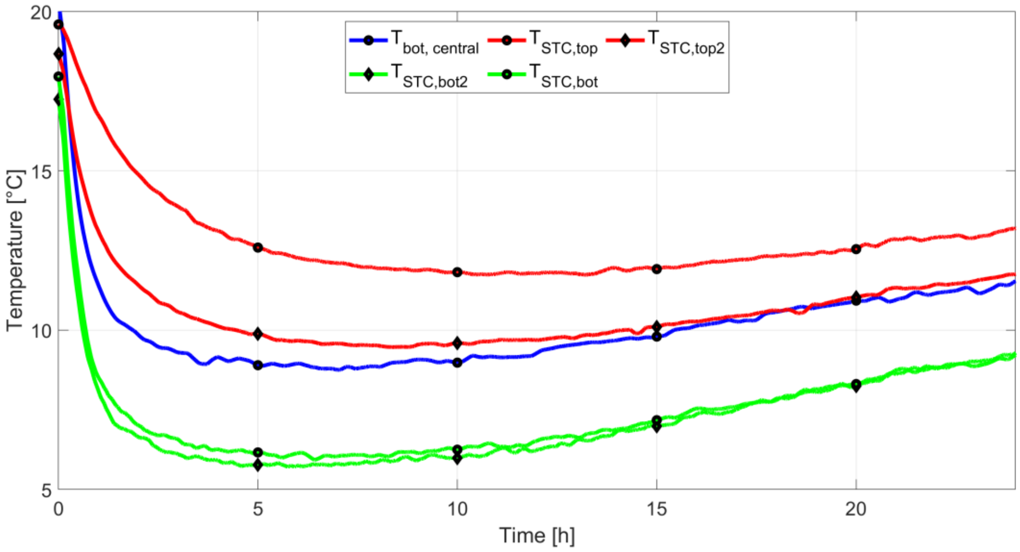


**Figure 9: Evolution of temperatures at the central outer bottom (blue) and inside the evaporator over time during the 24h commissioning test.**

The comparison of the temperature at the central outer bottom of the evaporator for the three tests shows similar cooling decreases, see Figure 10. The first test was stopped after approximately 1 hour, when the evaporator had reached 14 °C.

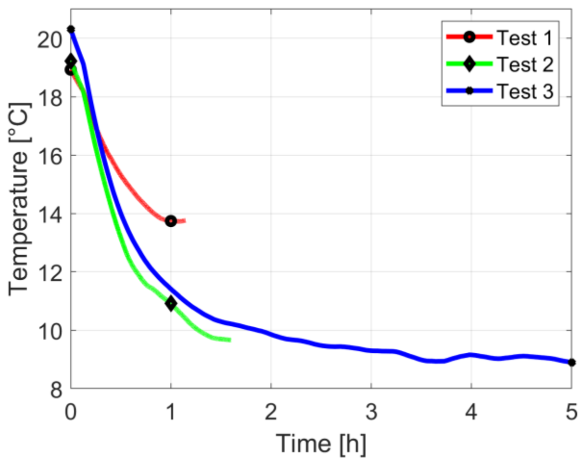


**Figure 10: Evolution of bottom temperatures of the evaporator during three commissioning tests.**

## 5. Conclusion and Outlook

In this work, the experimental setup of a novel facade-integrated adsorption system for solar cooling of buildings as well as first measurement results are presented.

The initial leakage tests confirmed that the system is vacuum tight as no pressure increases are found inside the main components adsorber, condenser and evaporator. Furthermore, it is found that minimum pressure levels below 1 mbar are reached by the evacuation process.

The first cooling tests with highly desorbed adsorbent zeolite 13X prove the practical functionality of the proposed cooling system. Minimum evaporator temperatures of around 6 °C are found and the outer bottom of the evaporator could be maintained below 10 °C for over 15 hours.

The future work will start with the regeneration process and will perform experiments with full daily cycles under various ambient conditions as well as different control strategies. Furthermore, the experimental results will be used to validate the simulation models.

## 6. Acknowledgements

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## Appendix

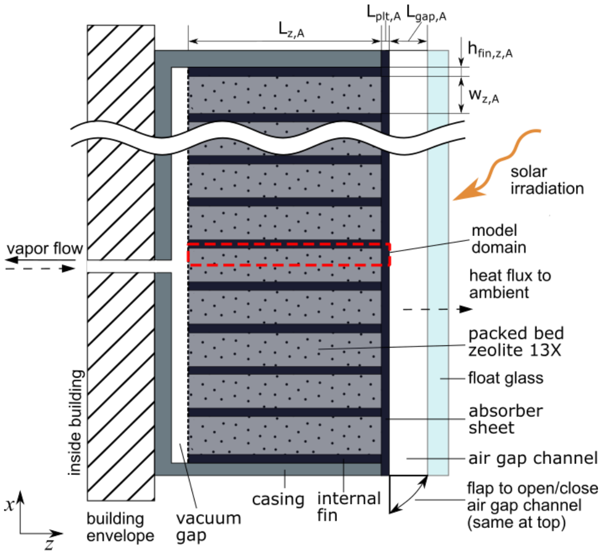


**Figure 11: Design scheme of the adsorber (cross-section side view). The scheme is not to scale as the height is approximately 0.9 m, while the width in z-direction is only approximately 9 cm. The absorber sheet is equipped with metal fins inside the air gap channel (not depicted). (Boeckmann et al. 2024)**

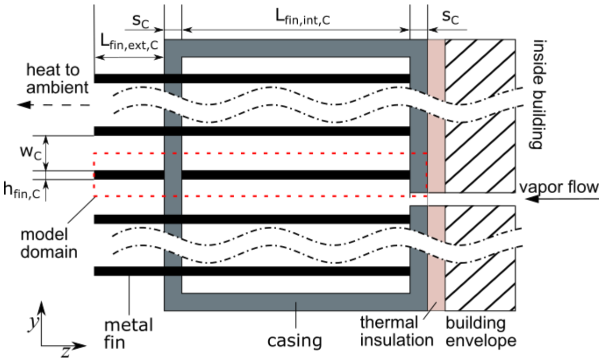


**Figure 12: Design scheme of the condenser (cross-section top view). The scheme is not to scale as the width in y-direction is approximately 1.1 m, while the depth in z-direction is only approximately 9 cm. (Boeckmann et al. 2024)**