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Activated building surfaces for space heating and cooling

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Abstract

Increasing internal loads and outdoor temperatures raise the need for comfort cooling, in particular in office buildings. A free-cooling method seldom considered is the heat rejection by activated components of the building envelope. An even more advantageous application is the heating and cooling operation with the same component. However, requirements for the surface properties may be different, resulting in optimisation potential depending on the prevailing load situation.

Therefore, a model has been developed and validated based on test rig measurements of absorbers with different selective coating. Subsequently, the model has been integrated in a system configuration suited for multifunctional operation with source storage, heat pump and thermally activated building systems. Heating capacities up to 600 W/m^2 are reached with good solar irradiation and selective coating. Cooling capacity ranges from 70 W/m^2 (selective) to 150 W/m^2 (non-selective) in clear sky nights.

Seasonal performance factors of 4-5 are reached in the space heating mode for the heat pump and solar combination and about 90% of the cooling demand can be covered in free-cooling operation with Zurich Meteoschweiz normal weather data depending on absorber properties.

Selective properties of the surface are less important as source energy for heat pump heating and for cooling in moderate nights. However, non-selective properties are important for radiation losses in hot summer nights, while selective coating increases the performance by direct solar heating. A further increase of the cooling capacity can be reached by wetting the surface.

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1. Introduction

Reasons for increasing cooling need, in particular in office buildings, are manifold, among them better insulation of buildings, increased comfort requirements in high performance buildings, increasing internal load due to more electrical equipment in use, large glazing fractions as well as last but not least the trend to rising outdoor temperatures by climate change. Therefore, comfort cooling becomes a necessity in many cases, in particular in office buildings. However, cooling loads can be covered efficiently by free-cooling methods, which have been increasingly introduced. Different free-cooling methods like ground-coupled free-cooling or nighttime ventilation exist, but each method has its particular limitations, like the energy balance of the ground for free-cooling by borehole heat exchangers and an adequate air exchange and sufficiently low outdoor temperatures for nighttime ventilation.

A passive cooling method seldom considered despite potentials is the nighttime heat rejection by activated components of the building envelope, which can act as heat exchanger to the ambient and radiator to the sky. This method gets even more beneficial, when the same activated surface can be used for heating purpose, as well. However, favorable properties for the space heating and cooling operation are not necessarily the same. Indeed, while losses of the surface are to be maximized for space cooling, they shall be minimize for heating purpose. On the other hand, heating occurs in wintertime at low altitude angles of the sun, leading to higher inclination angles for optimized surface yields, while in cooling mode, radiation to the night sky is maximized at high view factors to the sky requiring low inclination angles of the surface. Thus, optimisation potentials exist depending on the prevailing load situation. Therefore, in the project AKTIVA, the capacity of unglazed solar collectors are evaluated by test rig measurements for both space heating and cooling application. Based on the measurements, a model of the unglazed absorber is developed and integrated in a system configuration. System simulations are performed in order to evaluate key characteristics of the system performance in both heating and cooling mode.

2. Lab testing of solar absorbers

Lab testing has been performed at the Energy Research Lab (ERL) of the Institute of Energy in Building of the University of Applied Sciences and Arts Northwestern Switzerland in Muttenz. Fig. 1 shows the installed absorbers on the roof of the lab.



Fig. 1. Installed absorbers on the roof of the Energy Research Lab

Three unglazed solar absorbers with different degree of selective coating with long-wave emission coefficients of $\varepsilon = 0.15$ (selective coating), $\varepsilon = 0.3$ (faint selective) and $\varepsilon = 0.9$ (non-selective) in the infrared spectrum have been installed on the roof of the ERL. Tests have been performed at different weather conditions and with different inclination angles.

Fig. 2 shows the test results of the absorber. The absorber has been operated with a constant absorber inlet temperature of 25°C. During daytime, good solar irradiation conditions have persisted, followed by a clear sky in the beginning of the night. The selective absorber reaches the highest heating capacity for space heating operation during daytime of about 600 W/m^2 at maximum. Due to higher thermal losses, the non-selective absorber only reaches about 500 W/m^2, leading to advantages of the selective absorber in heating applications.

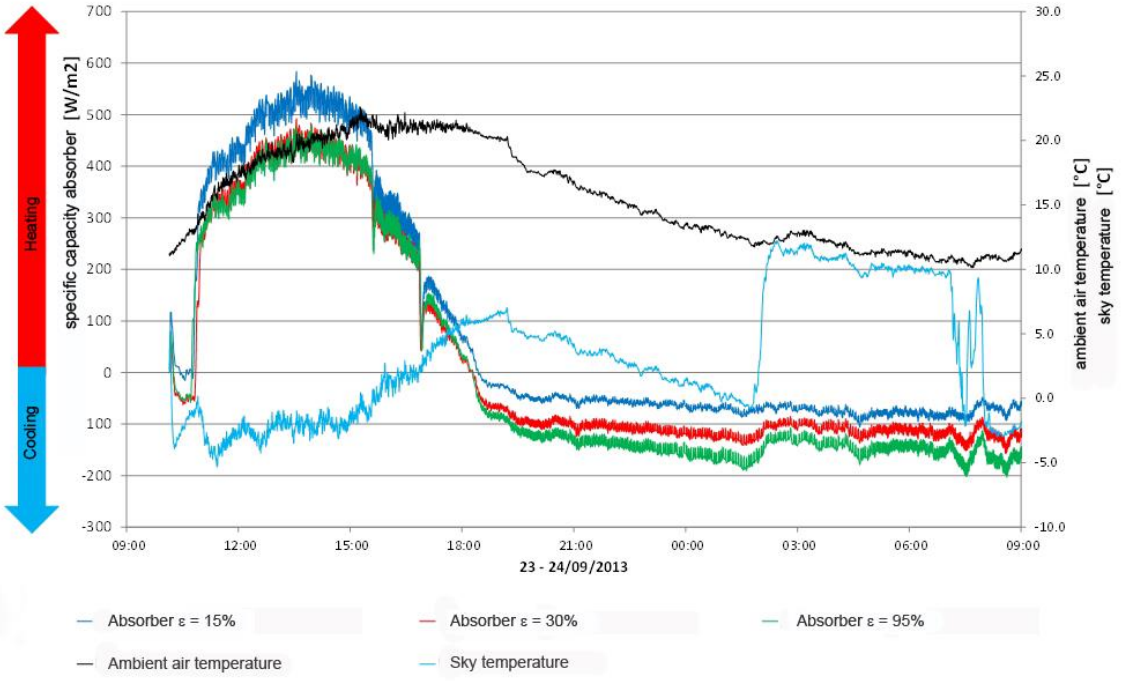


Fig. 2. Measurement results at good daytime solar irradiation and clear nighttime sky of the three absorbers with different selective coating

In clear nights the (fictive) sky temperature depicted in Fig. 2 has been calculated by longwave radiation measurements of a pyrgeometer and is significantly lower than the ambient air temperature, in the first nighttime hours by about 15 K. Therefore, even if the absorber temperature is in the range of the ambient temperature, the absorber can still reject heat by radiation to the night sky.

At good radiative properties of the non-selective absorber radiation to the night sky results in a cooling capacity of -200 W/m^2 for the non-selective absorber, while the capacity of the selective absorber is limited to values above -100 W/m^2. Thus, for cooling applications, the non-selective absorber has the better properties resulting in significantly higher cooling capacities.

At about 2 a.m., though, clouds come up, which is illustrated in Fig. 2 by the instantaneous rise of the sky temperature to almost the level of the ambient air temperature.

Thus, temperature differences are also smaller for the radiation and henceforth, the cooling capacity of the three absorbers is approaching each other and the surface property of the selectivity is of minor importance, since the radiation exchange with the sky is now limited by the higher sky temperature due to absorption of the clouds and a higher long-wave downward terrestrial radiation. The decrease of the cooling capacity of the three collectors is most prevalent for the non-selective collector, while the more selective collectors are hardly affected by the rising sky temperature.

3. Validation of absorber model

Based on the test results of the test rig measurements a model of the absorber has been implemented in the simulation tool Matlab-Simulink in order to perform system simulations with the measured component. Due to the changing capacities with changing weather conditions both in the space heating and cooling operation described in chap. 2, the model shall be used to derive seasonal performance values for a standard summer and winter operation.

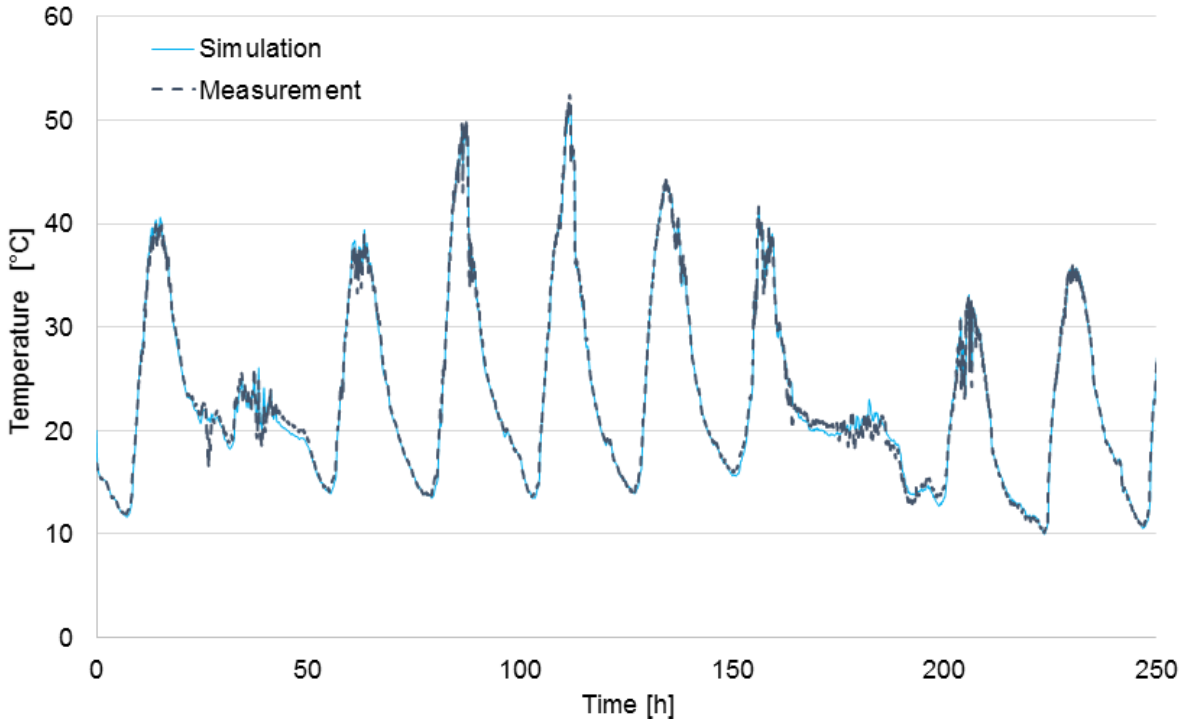


Fig. 3. Validation of the model with test rig data from the faint selective absorber of ε=0.3

The model is based on the model described in the collector test standard EN 12975 [1]. However, the normally identified coefficients from the collector testing have been replaced by physical expressions similar to the method described in Stegmann et al. [2] for PV/T collectors. After the implementation of the model, it has been validated for the different absorber types with the test rig data. Fig. 3 shows the comparison for the simulation of the faint selective absorber which confirms the good agreement of the simulated absorber model with the measured data.

4. System integration

After modelling the absorber has been integrated in a system model which is composed of components that can be used for multifunctional operation. The system configuration comprises a storage tank, a heat pump as well as thermally activated building systems (TABS) as emission system in the room zones.

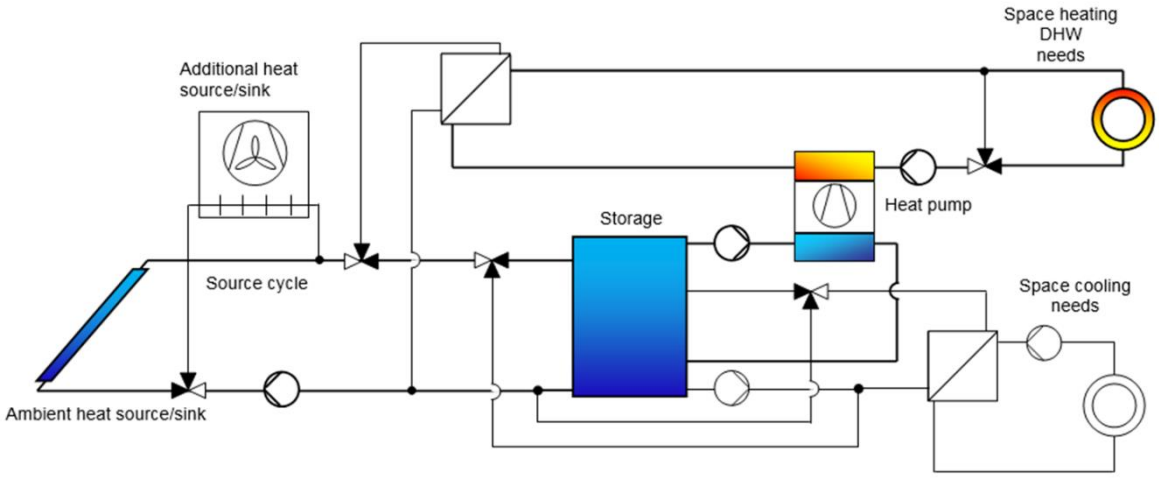


Fig. 4. Principle of the system integration, depicted in dedicated space heating mode with a solar absorber source and heat pump heating

All components can be used both in space heating and space cooling mode. In space heating mode, the absorber is used as solar heat source for the heat pump. The storage is integrated as source storage to store the heat source of the heat pump.

With solar radiation, the source fluid is heated by solar energy. In times of low solar irradiation the absorber is used as outdoor heat exchanger in order to extract heat from the ambient air. In order to prevent frosting, a water-glycol mix has been considered in the simulation. Alternatively, an ice storage would also be a suited source storage in heating application. Fig. 4 shows the principle of the system integration in dedicated space heating mode where the absorber is applied as a heat source of a heat pump. In times of high solar radiation when outlet temperatures of the absorber are higher than the supply temperature required by the TABS system, also a direct solar heating can be applied by bypassing the storage and the heat pump with the depicted heat exchanger.

In space cooling mode, the absorber is used as outdoor heat exchanger for nighttime heat rejection in free-cooling mode, which can be directly coupled to the TABS in the building zones. By recooling the building structure in the room zones at nighttime by the TABS, the cooling loads for the next day can be covered. Thereby, the building structure is used as cold storage to transfer the nighttime cooling energy to the daytime use.

The storage can be integrated as cold storage in the cooling operation, which helps to overcome adverse weather conditions in the night, e.g. situations with high nighttime temperatures or clouds. In case of insufficient cooling energy by the solar absorber, the heat pump can be applied in reverse mode as back-up chiller. Thereby, the heat extraction at the heat pump evaporator is used to cool down the cold storage, while the storage is used for cooling down the room zones. The condenser heat will be preferably used for DHW operation, or, in case of no heat demand, is rejected at the higher temperature level to the ambient by the absorber.

As further back-up system, an additional heat source, which can also be used as additional heat sink can be integrated in parallel into the system configuration. For space heating, also a back-up heater could be integrated instead.

5. Performance results in space heating mode

The lab test results give instantaneous capacity values, which, however, cannot reflect the long term performance due to the dependence on changing weather conditions. Therefore, seasonal simulations for the space heating and cooling operation have been accomplished with the validated model.

Simulations have been performed for two room zones in north and south orientation with single office use according the Swiss standard SIA 2024 [3] for the weather data of Zurich Meteoschweiz average year according to the Swiss standard SIA 2028 [4]. As extreme weather for the space cooling mode a warm summer of Lugano warm year according to SIA 2028 has been used. The room zones are equipped TABS positioned in the middle of the 30 cm concrete ceiling in a pipe distance of 0.2 m.

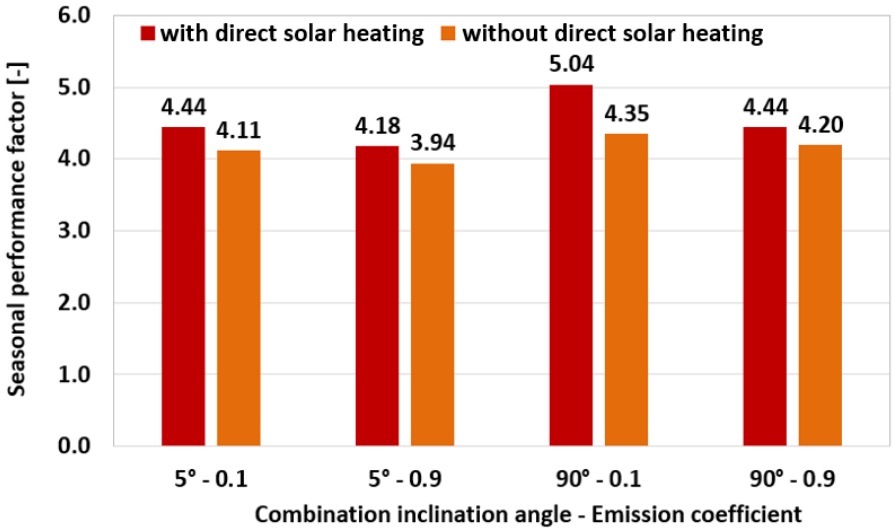


Fig. 5. Seasonal performance factor in space heating mode for extreme values of the absorber properties emission coefficient and inclination angle with and without direct solar heating

The design of the absorber is 0.33 m^2_{abs}/m^2_{ERA}, where the index abs denotes the absorber aperture area and the index ERA denotes the energy reference area. This corresponds to a three storey office building with entirely covered roof area by the absorber. The tested absorber types can be used as roof material. The storage design corresponds to 5 l/m^2_{ERA}.

Fig. 5 shows the seasonal performance factor (SPF) in space heating mode for extreme combinations of the emission coefficient of 0.1 (selective) to 0.9 (nonselective) and the inclination angle of 5° (flat roof) to 90° (façade integration).

For the results the option of a direct solar heating has been considered only in one case to evaluate if the additional hydronic expense for this option is justified. Without solar heating seasonal performance factors are in the range between 3.94 at adverse surface properties for the heating mode (low inclination, non-selective surface) and 4.35 for favourable properties (high inclination, selective coating).

These values are in the range of ground-coupled heat pumps. Recalculated to the heat source fraction, the degree of coverage of the solar energy is in the range of 75%-80%.

With the direct solar heating option, the SPF increases up to about 5, which makes up a difference of 0.7 to the SPF without direct solar heating for favourable properties.

Since the direct solar heating option depends on temperature levels higher than the required supply temperature for the TABS, it is clear that good properties of the absorber are needed to reach these required higher temperatures. Thus, the difference decreases with adverse properties to 0.25. Thus, it depends on absorber properties, if the hydronic expense seems justified.

6. Performance results in space cooling mode

Fig. 6 illustrates the configuration for space cooling operation with optional integration of the storage, where the absorber is used to reject the heat by radiation to the sky and by radiation and convection to the ambient air.

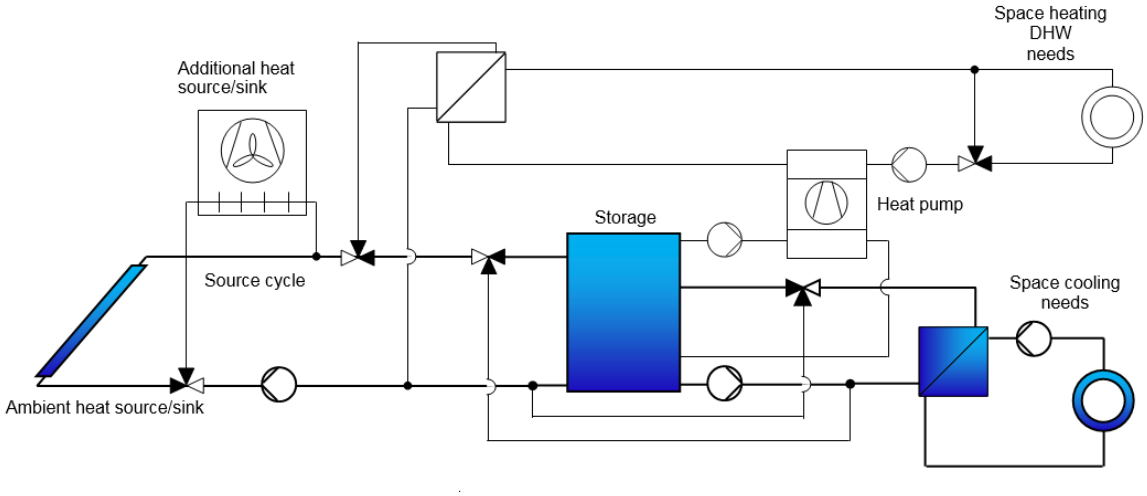


Fig. 6. System integration in space cooling mode with optional integration of the storage

The storage can be charged in situations of cooling loads lower than the free-cooling potential by nighttime cooling. The degree of coverage in free cooling operation for the different absorber properties is depicted in Fig. 7 with and without storage integration. In moderate summer climate of Zurich Meteoschweiz, high degree of coverage of above 90% for good absorber properties is reached i.e., high emission coefficient of the non-selective absorber and low inclination for better view factor to the sky.

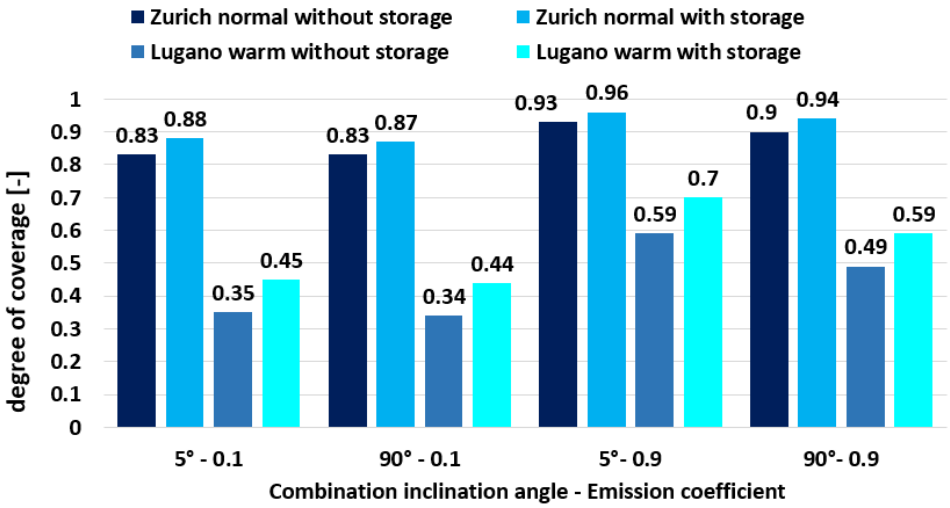


Fig. 7. System integration in dedicated space cooling mode with optional integration of the storage as cold storage

For rather adverse properties, still above 80% of the cooling needs can be covered by free-cooling. For these properties, the inclination angle is no longer of importance, since the radiative fraction is low due to the low emission coefficient of 0.1. In general, the properties are of minor importance in moderate climate, since the radiative fraction is low due to the low emission coefficient of 0.1. In general, the properties are of minor importance in moderate climate, since the convective fraction of the heat rejection is still high due to lower ambient nighttime temperature. In Zurich Meteoschweiz, for instance, 85% of the nighttime hours are below 15°C. Regarding the storage integration, the increase of the degree of coverage is limited to about 3% with good properties, and about 5% in rather adverse properties in moderate climate.

As comparison the extreme summer climate of Lugano warm year is included in the figure, as well. The degree of coverage notably decreases to about 60% with good absorber properties and to about 35% with rather adverse. Thus, the radiative fraction there is more important than in moderate summer climate, since the potential for convective heat rejection is limited. Due to the more restricted potential for free cooling in warm summer nights, the storage integrations yields a higher increase of the degree of coverage, since nights with adverse weather conditions can be supplied by buffered cooling energy from the storage. Thus, the increase of degree of coverage with integrated storage is in the range of 10%.

Fig. 8 shows the seasonal performance factor in the cooling mode, which is combined of the seasonal performance of the free-cooling mode, which only needs auxiliary energy for the pumping of the cooling fluid, and the EER of the back-up cooling by the heat pump in chiller mode. At favourable weather conditions and good absorber properties leading to high free-cooling degree of coverage, high performance factors of about 33 result, which is a typical range of free cooling applications. With decreasing free-cooling share and more back-up cooling, the performance factors decrease, however, even in extreme summer climate of Lugano warm, values above 8 are reached.

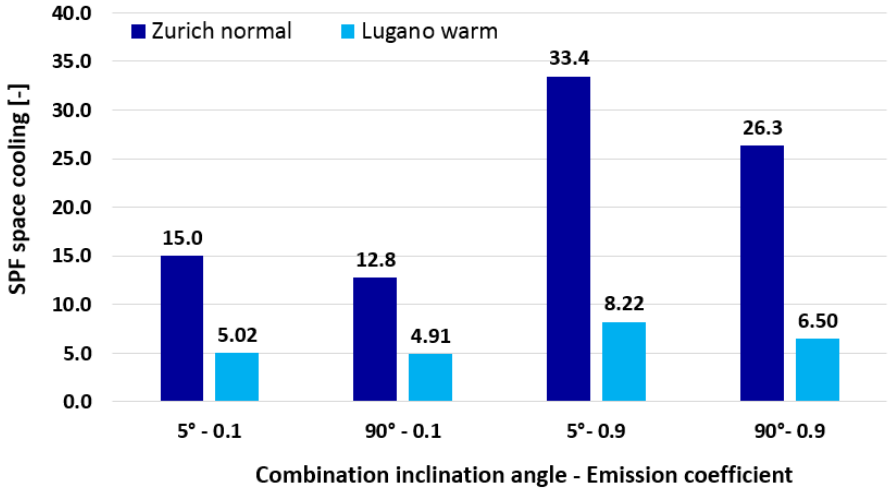


Fig. 8. Seasonal performance factor in cooling mode for different absorber properties and different weather conditions

Comparing the performance factors, it becomes clear that the emission coefficient has the higher impact on the performance than the inclination angle. If Zurich weather conditions are considered, the change of inclination angle from good to bad conditions reduces the SPF 33 to 26, while for changing emission coefficient, the value decreases to 15. Moreover, the SPF illustrates that even if the same degree of coverage is reached, as for the emission coefficient of 0.1 in Zurich weather, the SPF is lower, since longer running times of the pump are needed due to the reduced cooling capacity of the absorber.

7. Evaluation of the cooling capacity of wet surfaces

As shown in the preceding investigations, selective coating of the absorber improves the performance while being operated as a heat source due to lower thermal losses. However, selectively coated absorbers suffer from lower performance in cooling operation when the ambient temperature is near the supply temperature of the absorber and the convective share of the cooling power decreases. For multifunctional operation, the emission coefficient of the coating ideally should be a property with high emissivity in cooling operation and low emissivity in heating operation.



Fig. 9. Test rig with sprinkling installation

A method to increase the cooling capacity of the absorber both with and without selective coating is to wet the surface with a sprinkling installation. This increases the cooling capacity on the one hand by evaporation of water on the absorbers surface and on the other hand by increasing the emissivity of the selectively coated absorber surface by the water. The performance gain is more obvious at clear sky conditions where the radiation potential is higher. Fig. 9 shows the test rig on the roof of the energy research lab with the sprinkling installation.

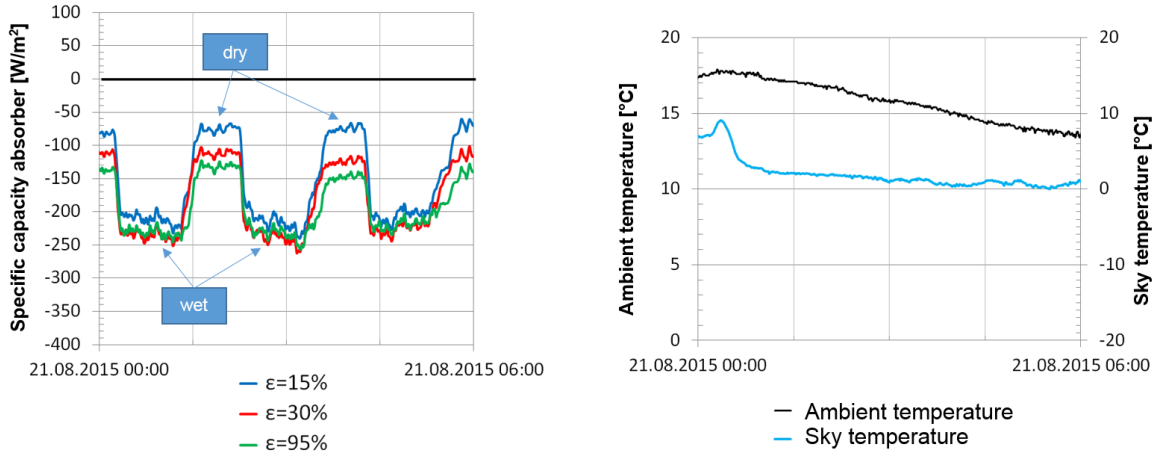


Fig. 10. Monitoring data of a night in August with clear sky, sprinkling interval [1 hour wet / 1 hour dry]

Fig. 10 depicts monitoring data of a summer night in August 2015. The absorber temperature is kept at 10 K above the ambient temperature. In order to obtain comparable results with dry and wet absorber surface, sprinkling is turned on and off in intervals of one hour while ambient conditions are almost identical. Starting with different cooling capacities caused by the different selectivity values of the absorbers in dry condition, the cooling power significantly increases with wet surface.

8. Discussion and conclusions

Based on test rig measurements of absorbers with different properties a simulation model of the absorber has been developed and validated. The model is integrated in a system configuration suitable for multifunctional operation in space heating and cooling in order to evaluate the key characteristics of degree of coverage and seasonal performance factors for the operation modes. Main components of the system configuration are a heat pump and thermal storage for space heating/cooling application. The heat pump is modelled by evaluating the capacity and COP based on the standard test results according to EN 14511 [6]. Regarding the cyclic behaviour, heating-up at the start and the cooling down in the end of the operation is considered by time constants. The storage is modelled as one-dimensional layer model including a mixing routine and has also been validated against measure data. The thermally-activated building systems are modelled according to Koschenz and Lehmann [7].

In space heating operation for buildings up to three storeys, i.e. an absorber design of 0.33 m^2_{abs}/m^2_{ERA}, seasonal performance factors of the heat pump operation with the only source energy of the solar absorber reaches values in the range of 4 without direct solar heating, which corresponds to typical values of ground-source heat pumps. With direct solar heating SPF of up to 5 can be reached. Selective properties are of minor importance for the absorber operation as heat source, since the absorber temperature is close to the ambient temperature, and thus, losses to the ambiance are low. However, in order to increase direct solar heating, which significantly improves

the SPF of the space heating operation, selective properties are essential in order to reach the necessary temperature level.

In space cooling operation, high degrees of coverage in the range of 80% to above 90% are reached. In moderate climate also the non-selective properties are not so predominant, since there is still potential for heat rejection by convection. In extreme summer climate, though, with higher night-time temperatures, the radiation fractions and thereby the impact of the non-selective properties are more important. The impact of the non-selective properties is also visible in the SPF of the cooling operation, which is significantly decreased from 33 to 15 with a change from non-selective to selective properties.

Summarizing, both in space heating and cooling operation high performance values are achieved with the absorber as only heat source and sink, respectively, for the considered system configuration and use case of a single office space equipped with thermally activated building systems. However, based on the prevailing load situation, optimization potentials exist regarding the properties of the absorber. While for space heating a selective coating yields the best performance results due to less heat losses to the ambiance and thereby increased temperature level, which is needed to augment a direct solar heating. On the other hand, in summer conditions with higher outdoor night-time temperatures, the radiative cooling effect gets predominant, since the heat rejection by convection is limited or may even counteract on the radiative heat losses, even during night-time, and thus a non-selective coating yields the better cooling capacities. In this study evaluations are limited to the use case of the single office space, which has been compared in moderate and more extreme summer conditions. A future task is thus to evaluate the overall energy input for space heating and space cooling at different absorber properties and for different use cases and designs. A promising approach to boost the cooling power especially in warm summer nights is wetting the surface with a sprinkling installation enhancing the cooling capacity of the absorber. The increased cooling capacity by a wet surface due to the additional evaporative cooling may also compensate decreasing cooling capacities at cloudy skies with rain. Thus, in clear night, radiative cooling is predominant, while in cloudy nights with rain, a missing radiative cooling capacity may be compensated by evaporative cooling of a wet surface.

9. Acknowledgment

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