Space Cooling Application with Unglazed Solar Absorber

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Abstract

Increasing outdoor air temperatures, rising number of electric devices and higher comfort requirements lead to significantly rising cooling demands. Free-cooling measures reach high efficiencies, which are limiting the electricity demand for cooling. In the SCCER EIP WP4 the reuse of treated wastewater for evaporative cooling is investigated. On the building level a system configuration with integrated evaporative cooling by outer building surfaces is developed, which can for instance be realized by unglazed solar absorbers or PV/T collectors and also cover the space heating and domestic hot water demand, enabling a cost-effective integration of the cooling operation. Simulations with boundary conditions according to the Swiss guidelines SIA 2024 and SIA 2028 for a single- and multi-family house as well as an office building according to the Swiss building directive MuKEn 2014 or better in Zurich yield high free-cooling fractions of 100% in residential application and from 80% to 100% in office use depending on the boundary conditions. By wetting the absorber the cooling capacity can be notably increased. Overall system performance is in the range of 4.5-6, which corresponds to ground-coupled heat pump system performance. The paper focuses on results of the multi-family house simulation.

Keywords: Space cooling, unglazed collector, multi-functional system layout, simulation study

1 Introduction

Currently, residential buildings are seldom cooled actively in central Europe, while in office buildings, there is already a cooling demand due to higher internal gains. However, recent studies indicate, that due to increasing outdoor air temperatures, rising number of electric devices and higher comfort requirements also in residential buildings, the cooling demand will increase significantly until the mid of the 21st century. In Settembrini et al. (2017) an increase of the cooling demand in residential buildings in Switzerland of 300% to 700% has been evaluated by simulations in the reference year of 2060. Since buildings have a long life cycle it is thus important to consider changes of the boundary conditions already in the planning phase. In addition to purely passive measures regarding the design of the building envelope, efficient cooling processes must also be developed and established in order to maintain comfort conditions, but to limit the electrical expenditure for cooling.

Passive cooling methods, often also denoted as free-cooling, have already been introduced, but more in the application of non-residential buildings. In residential buildings, free cooling methods are often limited to nighttime ventilation or ground-coupled free-cooling when a ground-coupled heat pump is used as heat generator. A possibility of free-cooling in residential buildings, which is not much applied so far, is the heat dissipation by activated outer surfaces of the building envelope, e.g. those installed with solar thermal components. These components, which are designed to generate heat, can also reject heat to the ambiance during nighttime operation, provided that there is a good thermal connection to the ambiance. In addition to pure heat dissipation to the outside air by convection, heat dissipation by infrared radiosity to the ambiance and particularly to the sky can be used, since a cloudless night sky has a significant lower equivalent sky temperature that is up to 20 K colder than the outdoor air temperature. Fig. 1 shows the cooling mechanisms that can be used for night-time cooling on the outer surfaces of buildings. The heat emission is especially favorable for uncovered solar components, which are in direct contact to the ambiance. An increase in the cooling capacity of these components can be achieved by an additional evaporative cooling, if the surface of the components is wetted with water. In order to have a sustainable water source, reuse of decentralized treated grey- and wastewater is investigated as water for wetting the absorber.

doi:10.18086/eurosun2018.01.14 Available at http://proceedings.ises.org

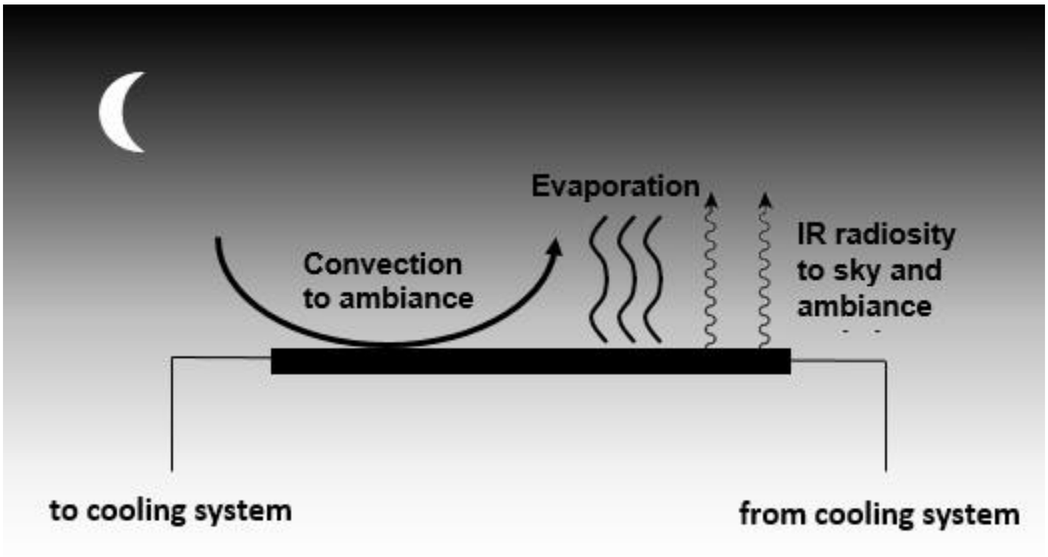

Fig. 1: Different cooling mechanisms on building outer surfaces

2 Method

In order to evaluate the feasibility of free-cooling by the outer building surfaces, simulation studies were carried out for residential and office buildings. In this publication, the investigations of the residential buildings, in particular in multi-family building, are presented. Results for the office buildings examined show that high free-cooling rates of 80% to almost 100% can be achieved for Zurich Meteoschweiz weather station according to the Swiss guideline SIA 2028 (2018) and boundary conditions of use according to SIA 2024 (2015), depending on comfort requirements and properties of the outer building surface.

The simulations for residential buildings were carried out for a single- and multi-family house. For both types of buildings, energy-efficient new buildings have been considered that meet the requirements of the Swiss building directive MuKEn 2014 (2015).

2.1 Building parameters

The single-family house has an energy reference area of 200 m^2. The U-value of the outer walls with $U_{AW} = 0.17$ W m^{-2} K^{-1} corresponds to the requirements of the Swiss building directive MuKEn 2014 (2015). The window fraction of 40% is evenly distributed across all façade orientations. The windows are triple glazed with an U_g-value of 1.0 W m^{-2} K^{-1} and a low fraction of the frame of only 10%. The g-value of 0.5 is in the typical range for triple glazing. For shading, variants are calculated that are to reflect the user behavior. With optimal shading, from 200 W m^{-2} irradiance and a room temperature of 23.5 °C, the total energy transmission is reduced to a g-value of g = 0.1. Irradiance of 400 W m^{-2} and 600 W m^{-2} are considered as variants for non-optimal shading and 1000 W m^{-2} as unshaded case. For the hot water consumption, 150 l or 37.5 l $person^{-1}$ with a useful temperature of 55 °C were used constantly throughout the year, which corresponds to an energy consumption of 2900 kWh or 14.5 kWh $m^{-2}a^{-1}$.

The multi-family building has 5 stories with a total of 10 flats. The total energy reference area is 1500 m^2, resulting in approx. 150 m^2 per flat. The U-value of the outer wall is with U_{AW} =0.185 W m^{-2} K^{-1} just above the limit value according to MuKEn 2014 (2015), and the U-value of the triple-glazed window with a frame proportion of 10% with U_g = 1.2 W m^{-2} K^{-1} is also slightly higher than the requirement. The g-value is 0.5, which is reduced to 0.14 when shading is activated. Shading is controlled dependent on the façade orientation. The activation of the shading of 200/400/600 W m^{-2} irradiance is also varied for multi-family houses in order to model different user behavior. The occupancy of the flats with 5 persons or a person area of 30 m^2 $person^{-1}$ is higher than in a single-family house with a person specific area of 50 m^2 $person^{-1}$. Hot water consumption is assumed to be a slightly lower consumption of 30 l $person^{-1}$ at a hot water temperature of 55 °C.

The residential buildings are equipped with mechanical ventilation and heat recovery, which has a temperature change coefficient of 80%. In summer mode, heat recovery is reduced to 10% for modelling a summer bypass. The residential buildings are also both equipped with floor heating, which corresponds with 0.1 m pipe spacing to a rather large dimensioned floor heating, which enables low flow temperatures and thus creates favorable conditions for renewable energy use. The floor heating serves as a transfer system for both heating and free-cooling operation.

2.2 System configuration

The building technology consists of a solar absorber, which is connected to a water-glycol source storage tank and serves as the only heat source for the heat pump, which extracts the source heat from the source storage tank. The heat pump operates in both heating and hot water mode. If the temperature level of the solar absorber is high enough, the hot water generation can also be switched over to the absorber and be carried out directly with the solar absorber. In this study a selective absorber is considered, which can reach the hot water temperatures in summer operation due to the reduced radiative losses at higher temperatures. Furthermore, both a buffer tank for heating operation and the hot water tank are integrated. In cooling mode, the source storage is used as a cold storage. Then, the absorber circuit is operated during the night for heat losses to the ambiance in order to cool down the storage tank. When charging the storage tank with the heat extracted from the building by the floor heating, the comfort limit of a floor surface temperature of at least 19 °C must be considered. Tab. 1 summarizes the parameters of the single-family and multi-family house.

Tab. 1: Building and system parameters for the single-and multi-family building

Building and system parameters	**Single-family house**	**Multi-family house**
Residents/People	4	50
Window fraction	40%	40%
Energy reference area (ERA) [m²]	200	1500
Annual heating demand [kWh m^{-2}_{ERA}]	25	15
Annual hot water demand [kWh m^{-2}_{ERA}]	14.5	19.5
Annual cooling demand [kWh m^{-2}_{ERA}]	4-6	4-6
Absorber area [m^2_{abs}]	11-18	71-178
Source-/cold storage [l m^{-2}_{ERA}]	5.0	3.3

The hot water demand of the multi-family building exceeds the heating energy demand (see Tab. 1) due to a low space heating demand of 15 kWh m^{-2} a^{-1} on average between the flat, ranging from 9.3 kWh m^{-2} a^{-1} of a flat on the third floor in south orientation to 27.4 kWh m^{-2} a^{-1} of a flat in north orientation on the top floor. The low space heating demand is due to the lower area volume ratio of the multi-family house. In addition, the multi-family house has a higher occupancy with 30 m² $person^{-1}$, which increases the hot water requirements and also lowers the space heating needs due to about two-thirds higher internal gains compared to the single-family house. However, the loads for equipment and lighting remain the same. The cooling requirement is with an average of 4 kWh m^{-2} a^{-1} still moderate and ranges from 2.6 to 4.8 kWh m^{-2} a^{-1}. It is slightly lower than for a single-family house, partly for similar reasons as for heating, e.g. due to the smaller outer surface area compared to the energy reference area and also due to slightly smaller window area.

3 Results

In the following, the results for the multi-family building are discussed in more detail. Variation carried out for the multi-family house are

- Variation of the absorber area
  71 m^2 (40 absorbers), 107 m^2 (60 absorbers), 142 m^2 (80 absorbers), 178 m^2 (100 absorbers)
- Variation of shading activation of 200/400/600 W m^{-2}. Additionally, an unshaded case (activation at 1000 W m^{-2}) is considered.
- Variation of the weather boundary condition of the weather station "Zurich Meteoschweiz" normal and warm annual data sets

3.1 Seasonal performance factors of the heat pump in multi-family house

Fig. 2 shows the seasonal performance factors (SPF) of the heat pump both in space heating and domestic hot water (DHW) mode and the combined SPF. In space heating mode, the SPF of the heat pump is in the range of 4.3 and can be increased to a value of almost 5, if the absorber area is increased. A larger absorber area increases the source temperature for the space heating operation, which leads to higher performance factors. The SPF of the heat pump in DHW mode lies between 2.8 and 3.0. The increase of the SPF in the DHW mode is only moderate, since with higher absorber area, the fraction of direct DHW production by the absorber is increased, so that the heat pump has to produce the higher DHW temperature levels, which compensates the better source temperatures. The overall SPF for space heating and DHW operation is between 3.5-3.8 which approaches the SPF of ground source heat pumps, which lie in the range of 4 in recent field monitoring projects (Guenther et al., 2014). For a change of the weather conditions to Zurich Meteoschweiz warm year, the SPF of the heat pump is slightly increased by 0.1 due to the better source temperature conditions.

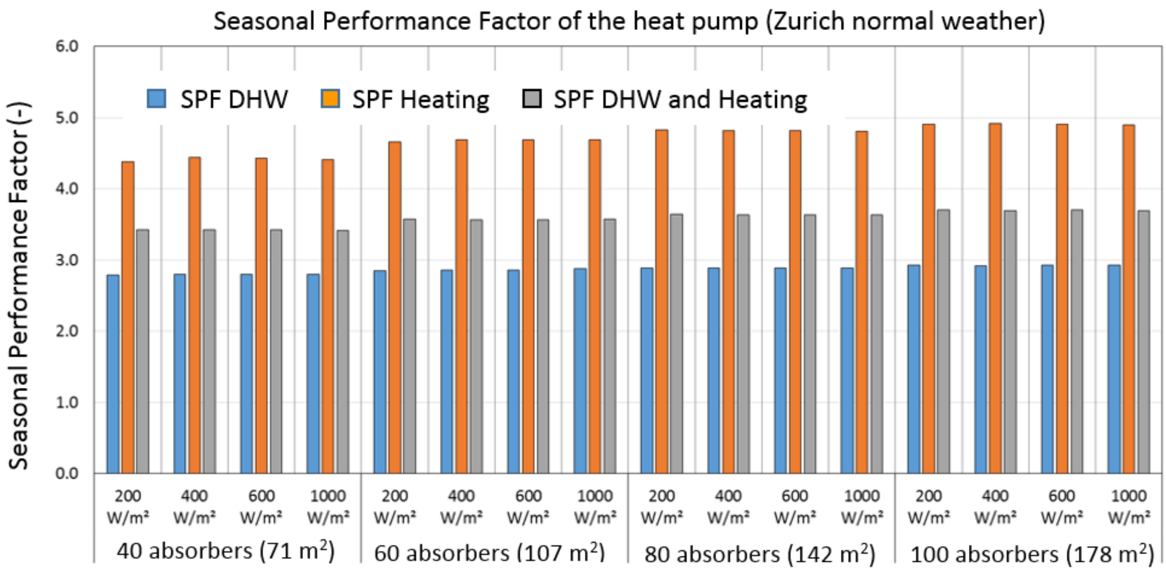

Fig. 2: Seasonal performance factors for the different operation modes, activation of shading and absorber areas

3.2 Seasonal performance factors generator in multi-family house

Fig. 3 shows the seasonal performance factors SPF generator, with includes both generator systems, the heat pump and the direct solar DHW operation of the absorber. The figure is split-up into the DHW mode only and a combined SPF for all operation modes including also a free-cooling operation by the absorbers. Due to the direct solar DHW operation, the SPF generator in the DHW mode is notably increased. For the smaller absorber area, a SPFgen of 4.0 is reached, which increase with higher absorber areas to 4.6 in comparison to 3.0 of the SPF of the heat pump.

The overall SPF of the system of all operation modes including also the free-cooling operation of the absorber is notably increased, as well. The effect of the cooling mode can be seen in the variation of the shading. The higher the cooling load the higher the overall seasonal performance, since the cooling demand can be covered very efficiently with the free-cooling operation. The efficiencies in cooling mode are in the range of 20 depending on the nighttime weather conditions. With the largest absorber area, an SPF of 5 is reached compared to an SPF of 3.8 of the heat pump. Direct solar DHW shares are in the range of 40%.

The change of the SPF generator for a change to Zurich Meteoschweiz warm year is more distinct than for the heat pump. Due to a higher solar DHW yield, a higher fraction of cooling demand and better source temperatures, the overall SPF generator is in the range of 6.

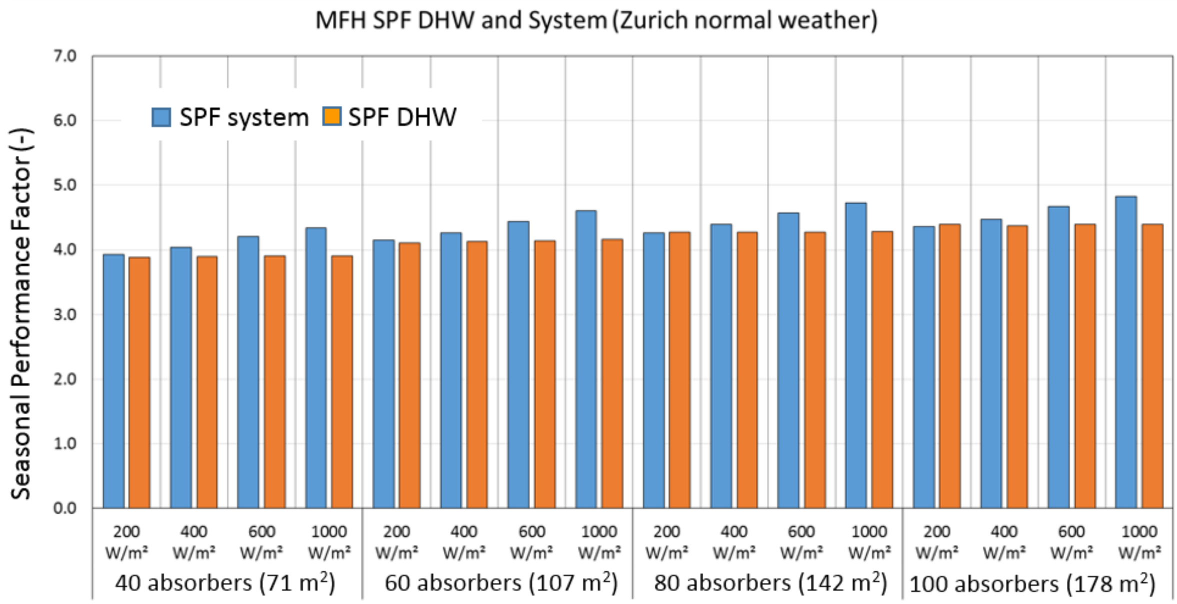

Fig. 3: Seasonal performance factors generator for the different operation modes, activation of shading and absorber areas

3.3 Comfort multi-family house

The comfort evaluation presented is based on the operative room temperature and the smallest absorber area of 107 m^2, since relative humidity cannot be influenced by the cooling operation and a smaller absorber area limits the cooling capacity. Fig.4 shows the hourly operative temperature within the limits of SIA 180 (2014) for air-conditioned buildings, even though no active cooling or air-conditioning is applied in the buildings. However, the criteria are stricter than for window ventilated buildings, where adaptive comfort criteria apply.

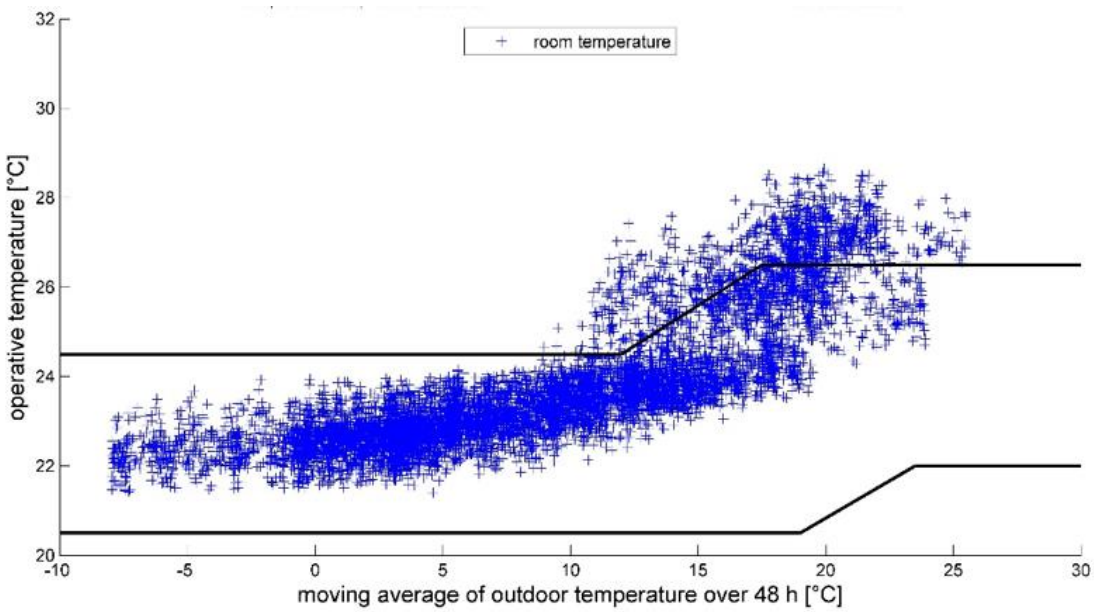

Fig. 4: Operative temperature for optimally shaded building without free-cooling according to SIA 180 (2014)

In Fig. 4, the variant with optimal shading operation at 200 W m^{-2}, but without free-cooling operation is depicted. In the winter operation the building is kept in the temperature range between 22 °C-23 °C, which is in the middle of the range of comfortable temperatures and often found as winter temperature range in field monitoring projects. However, in the summer operation, the shading cannot avoid violation of the comfort range. Already in the transitional period overheating occurs, while in the summer, the temperature reaches values above 28 °C.

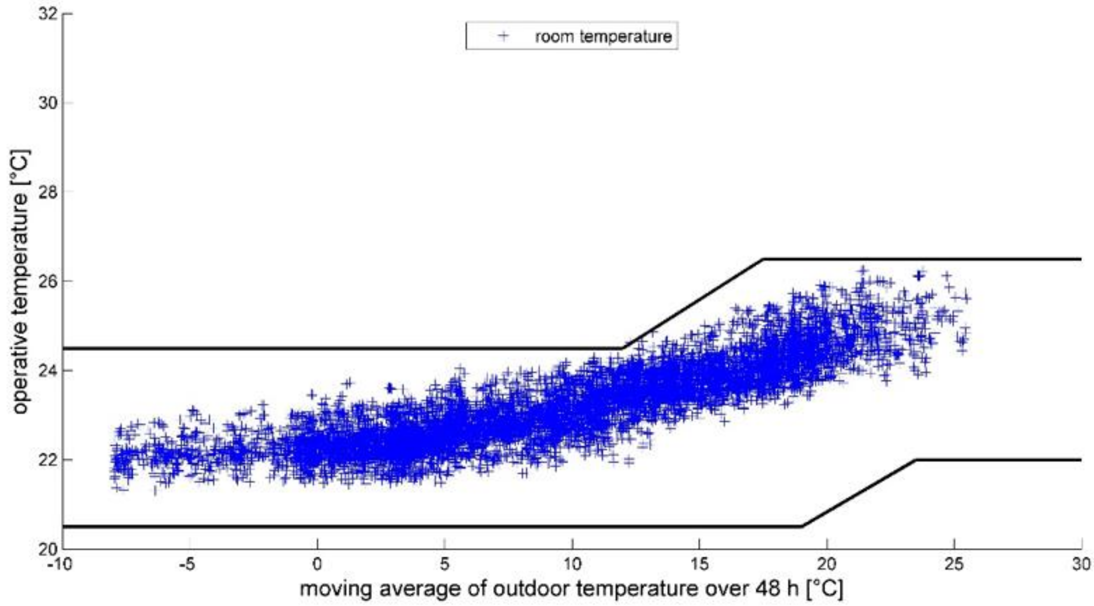

Fig. 5: Operative temperature for optimally shaded building with free-cooling range according to SIA 180 (2014)

Fig. 5 shows the variant with optimal shading and additional free-cooling operation. The overheating can be notably reduced, so that all hourly operative temperatures are in the comfortable range. The critical temperatures, which are approaching the comfort limit, are rather in the transitional period, i.e. in the summer operation, there is even a distance to the comfort limit. Thus, the free-cooling operation can compensate within limits a non-optimal shading without violation of the comfort range.

3.4 Results for the single family house

The results for the single family house resemble the results of the multi-family house. So, only a brief overview is given in the frame of this publication. Performance values vary slightly from the multi-family building due the different loads and design values. The seasonal performance of the heat pump reaches an SPF of 4 in space heating operation and an SPF of 3 in DHW operation, leading to an overall performance factor between 3.5–3.8 dependent on the absorber size. The overall SPF of the generator including the direct solar DHW production and the free-cooling operation reaches values up to 5 depending on the absorber size.

The comfort in terms of the operative temperature in the single family house is also similar to the multi-family house. In summer, the shading alone is not enough to stay entirely inside the comfort boundary, 340 overheating hours occur in summer with maximum temperatures around 28.5 °C. With additional free-cooling, however, the overheating can be completely avoided and there is a remaining temperature difference to the upper comfort limit. However, free-cooling only without any shading (shading activation at 1000 W m^{-2}) also leads to 260 overheating hours, of which, though, only 110 occur in the summer. The other150 overheating hours occur in the transitional period, which implies an optimization potential of the control of the free-cooling operation, since the potential of heat rejection to the ambiance should be high enough in the transitional period. Operative temperatures in winter are around 22 °C and thereby around the optimal winter temperature. Different to the design of the absorber in the multi-family house, in the single family house at low absorber size, source temperatures below the operation limit of the heat pump can occur at cold outdoor air temperatures. With a larger design of the absorber, though, source temperatures are increased and stay above the operation limit of the heat pump. With the absorber design for the multi-family building, no problems with the lower operation limit of the heat pump were observed.

4 Discussion

Both in single family and in multi-family buildings the feasibility of the system operation including the free-cooling is confirmed. The systems reach good performance values in the range of an overall performance between 3.5 – 3.8 for the heat pump and up to 6 with absorber operation and higher cooling demand. The comfort conditions according to SIA 180 (2014) for air-conditioned buildings can be kept with a combination of shading and free-cooling operation. In the following, different aspects are discussed in more detail.

4.1 System configuration

The system configuration is chosen in a way that all system components can be applied in multifunctional operation, both for space heating and the space cooling. The absorber is used as heat source in winter and heat sink in summer. The heat pump is used for the heat production for space heating and DHW operation, but can also be used in back-up operation for the space cooling mode, although this operation mode has not been applied in this study. The heat emission in winter and heat extraction in summer is both accomplished by the floor heating and the source storage is used as heat storage in winter and cold storage in summer. There are even synergies between the operation mode, e.g. in DHW mode, the source storage is cooled down by the heat pump. In winter operation, this enables a longer operation time for the solar absorber, in summer operation, the heat extraction of the evaporator in DHW mode is used as back-up cooling for the source storage. However, in summer operation, a large fraction of 70 – 90% of the DHW demand can be covered directly by the absorber and the efficiency of the free-cooling operation is higher than the efficiency in simultaneous operation of the heat pump, which leads to high overall performance factors.

4.2 System performance

The seasonal performance factor of the heat pump operation is in the range of ground-coupled heat pumps, which reaches a value of 4.15 on average according to current field monitoring (Guenter et al., 2014). Depending on the DHW share the combination with solar DHW production even reaches higher performance factors. The high performance values of the free-cooling operation in the range of 20 can further increase the overall efficiency at higher cooling fractions. The given performance and comfort evaluations, though, refer to a distinct design of the systems, which has not been varied in the frame of this study. Design changes in the system components can thus improve the performance and comfort reached by the system configuration. For this study the design of the source and the DHW storage were kept constant. With larger design of the source storage, for instance, more energy can be stored to overcome adverse weather conditions. By better source temperatures, also the system performance can be improved. In fact, if the source storage is designed too small, problems with the operation limit of the heat pump may occur. There are also system improvements regarding the control, so optimization on different levels are possible.

4.3 Free-cooling operation

By the free-cooling operation, the comfort according to SIA 180 (2014) can be kept efficiently, which would not be possible with shading only. Despite the building is not actively cooled the comfort requirements for air conditioned buildings can be achieved. Thereby, the free-cooling operation reaches high performance values in the range of 20. Cooling capacities reached with the absorber are in the range of 50 W m^{-2}-200 W m^{-2} depending on the weather conditions at nighttime. In order to maximize the DHW operation, a selectively coated absorber with an IR emittance of $\varepsilon_{IR} = 0.15$ has been used for this study. Typically, a selectively coated absorber is not well suited for a cooling operation, since the IR-emission to the sky during nighttime operation is strongly inhibited by the selectivity. However, in this case, a wetting of the absorber has been considered, which significantly increases the IR emittance to that of water, and additionally contributes to the cooling capacity by evaporative cooling. Simulation results show an increase of the cooling capacity by about 50% of the wet absorber. While in the considered residential buildings, the space heating operation is dominant and the cooling demand can be entirely covered by free-cooling, if shading is adequately operated, in office buildings, cooling may become the predominant load.

5 Perspective

In the frame of the feasibility study the capacity of the system integration has been approved for the application in residential buildings. In the research project as part of the Swiss Competence Center of Energy Research on Efficiency of Industrial Processes Work package 4 (SCCER EIP WP4) further investigations on the operation of the evaporative cooling with treated grey-/wastewater are planned. Thereby, requirements on the water quality with regard to scaling, fouling, odors and hygienic requirements are investigated and necessary water flows for the prevention of the above issues are assessed. Moreover, investigation for an optimized wetting of the outer surface as well as capacity and performance evaluation shall be accomplished, and also other components like PV/T collectors shall be investigated, which are delivering also electrical energy besides the thermal yield. However, with PV/T, there may be limitations regarding the reachable temperature level for DHW operation.

The research project is financially supported by the Swiss Innovation Agency Innosuisse and is part of the Swiss Competence Center for Energy Research SCCER EIP.

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