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CoolShift – Cooling of buildings by chiller-assisted nocturnal radiation and convection

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Abstract. A novel approach for cooling an office building is numerically evaluated. PVT collectors are used for nocturnal radiative and convective cooling. A TABS ceiling serves as thermal storage. If the free cooling power of the PVT collectors is too low, it is boosted by a chiller raising the collector temperature. While the energy efficiency improves compared to a conventional daytime chiller cooling system, the room temperature cannot always be kept in the desired band. Furthermore, the PVT collectors stay cooler than comparable PV modules during the day, increasing the electricity generation.

1. Introduction

Radiative heat exchange between earth and space results in an equivalent black-body temperature of the clear sky, which can be significantly below the ambient temperature on the ground. This effect has been used for millennia to produce ice, even at ambient temperatures above 0 °C [1]. It can also be used to supply chilled water for space cooling with rooftop radiators. Previous studies conclude that the cooling power per radiator area is too low to use it on its own [2]. One approach to address this problem is to use radiative cooling for pre-conditioning for a conventional chiller [3][4]. In contrast, our approach is to use a chiller to elevate the radiator temperature, thus increasing both radiative and convective cooling power. This eliminates the need for a rooftop fan, which consumes electricity and emits noise.

2. Methods

A room of an existing office building according to the standard Minergie-P is modeled in Matlab/Simulink, using the CARNOT Toolbox, version 6.3 [5]. Three cooling systems are modeled: Nocturnal ventilation cooling, a traditional air/water chiller with ceiling-mounted cooling panels, and the CoolShift system using photovoltaic-thermal collectors (PVT) for chiller assisted nocturnal radiative and convective cooling in combination with a thermally activated building systems (TABS) ceiling. If the ambient conditions allow it, the chiller is bypassed for free cooling. All three systems are simulated with local weather data from April 15 to September 30. The April days are settling time and discarded for the analysis.

2.1. Climate, Room and Internal Loads

Weather data from Basel-Binningen [6] with an annual average ambient temperature of 10.5 °C and an annual solar irradiance of 1035 kWh/m^2 is used. The room is in the south-western corner on the 3rd floor and measures 43 m^2 with 18.3 m^2 of window area. An internal load of 640 W is assumed to heat up the room between 8:00 and 17:00.

2.2. Ventilation, Shading and Heating

Daytime ventilation runs from 7:00 to 20:00 with an air exchange rate of 44.9 m^3/h and a heat recovery of 80 %. The ventilation bypasses the heat recovery for free cooling from midnight to 6:00, if the room temperature is at least 8 K above the ambient temperature. Free cooling is triggered by a room temperature above 24 °C with a target temperature of 20 °C. The windows are externally shaded if the solar irradiance on the window surface exceeds 180 W/m^2. The shading attenuates the irradiance by 80 %. The remaining 20 % account for the remaining light still passing through the shading as well as heat transfer between the hot shading elements and the window. An idealized heating system keeps the room temperature between 21 °C and 22 °C. However, its influence for the evaluated months is negligible.

2.3. Chiller Model

The compressor has a power between 120 W and 400 W. Based on the measurements of [7] and the modeling approach of [8], the Carnot efficiency is simplified to a constant 40 % for the calculation of the energy efficiency ratio (EER) and thus the thermal power. The ΔT at the condenser and evaporator are also constant [8], based on the chiller type. A PI controller sets the cold-side output temperature.

2.4. Conventional Cooling

The conventional cooling system consists of an air/water chiller supplying water 4 K below the room temperature to 12 radiant ceiling panels of the type Kigo Swiss [9] with a total area of 24.6 m^2. The room temperature is kept in a 2 K band below the upper limit in **Figure 1**. A 48 h moving average of the ambient temperature is used. For comparison with the PVT collectors used for CoolShift, a pure photovoltaic (PV) installation with the same electrical properties is modeled.
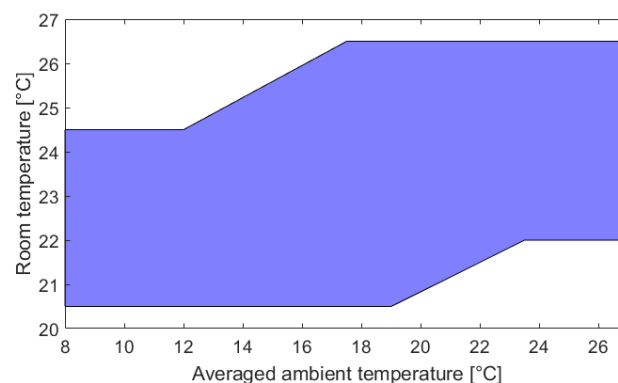

Figure 1: Room temperature band in dependence of averaged ambient temperature

2.5. CoolShift

The hydraulic scheme for CoolShift is shown in **Figure 2**. For heat rejection, four PVT collectors of the type SOLINK [11] with a total area of 7.92 m^2 are used. The collectors are facing south with a 30° inclination and are supplied with a 70/30 % water/glycol mixture. In order to provide sufficient thermal storage, the ceiling panels used for the conventional cooling are replaced by a TABS ceiling. The chiller supplies water 2 K below the room temperature. Unlike the reference systems, the nocturnal ventilation cooling is disabled.

CoolShift is controlled as follows: The system is enabled from midnight to noon, if the building is in cooling operation (defined in chapter 3.1) and the surface solar irradiance is below 50 W/m^2. It runs until a room temperature 4 K below the upper limit of the room temperature band is reached. A model of the PVT collectors estimates the theoretical free cooling power at any moment. If it is below a certain threshold (P_{switch}), the chiller is switched on.
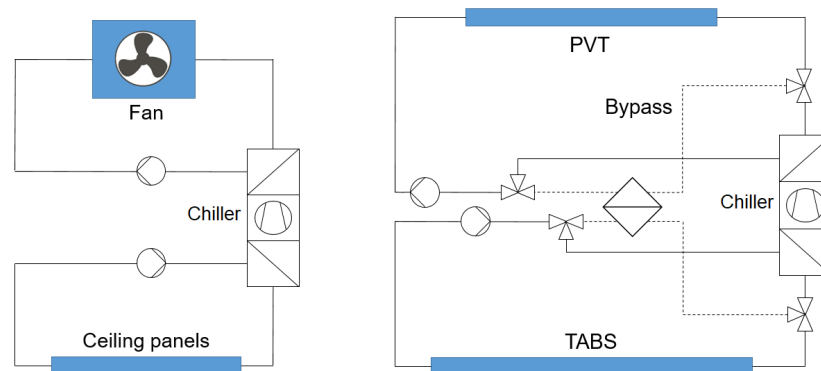
Figure 2: Hydraulic scheme for conventional cooling (left) and CoolShift (right)

2.6. Evaluation Criteria

The quality of the room temperature control is quantified by integrating the room temperature deviation from the band specified in **Figure 1** between 8:00 and 17:00 for each day. **Table 1** lists the thermal and electric key performance indicators. The cooling energy is split into three components: ventilation cooling (VC), PVT free cooling (FC) and chiller (including pumps) cooling (CH). For the ventilation cooling, the electric and thermal powers are only integrated if the ventilation contributes to the cooling. The electric surplus is defined as PV generation minus total cooling electricity.

$T_{deviation}$	Temperature band deviation	$E_{el,VC}$	Electricity ventilation cooling
$Q_{cool,tot}$	Total thermal energy cooling	$Q_{cool,VC}$	Thermal energy ventilation cooling
$E_{el,cool,tot}$	Total electricity cooling	$E_{el,CH}$	Electricity chiller
EER_{sys}	System EER	$Q_{cool,CH}$	Thermal energy chiller
E_{PV}	PV generation	$E_{el,FC}$	Electricity free cooling
$E_{el,surplus}$	Electric surplus	$Q_{cool,FC}$	Thermal energy free cooling

Table 1: Key performance indicators

3. Results

3.1. Calibration of the Room Model

The room model with daytime ventilation and internal load is simulated over one year. The room temperature is controlled with an idealized heating and cooling system keeping a room temperature between 21 °C and 0.5 K below the upper limit of the blue area in **Figure 1**. From this simulation, the ambient temperature limits for the main simulations are determined to be 11 °C for heating operation and 13 °C for cooling operation. The heating values in **Table 2** are rather low, due to the good thermal insulation in combination with a high internal load and solar gains.

Mode	Room	Per area
Heating	647 kWh/a	15.0 kWh/m²a
Cooling	433 kWh/a	10.1 kWh/m²a

Table 2: Heating and cooling energy per year

3.2. Comparison of Cooling Systems

Table 3 shows the key performance indicators for the two reference systems and four CoolShift variants: No chiller and three different switch points (P_{switch}, see chapter 2.5). As expected, the nocturnal ventilation variant has excessive temperature band deviations but low electricity consumption. In comparison, the conventional cooling has no temperature band deviations. The delivered cooling energy is higher than for the more idealized calibration simulation in chapter 3.1, because the room temperature is kept in a 2 K band below the upper limit instead of a set point 0.5 K below.

Regarding the CoolShift variants, the delivered cooling energy is higher than with the conventional cooling. This can likely be attributed to two causes: Thermal losses resulting from the time shift between cooling supply and demand as well as occasional over-cooling, because the cooling target temperatures are set anticipating a hot day. CoolShift without the chiller has a high EER, but also significant temperature band deviations. With increasing chiller operation, the temperature band deviations quickly drop to zero, along with a decreasing EER. Free cooling supplies most of the cooling energy for all CoolShift variants.

		Nocturnal ventilation cooling	Conventional cooling	CoolShift, no chiller	CoolShift, $P_{switch} =$ 500 W	CoolShift, $P_{switch} =$ 750 W	CoolShift, $P_{switch} =$ 1000 W
$T_{deviation}$	Kh	4031	0.0	24.7	2.2	0.1	0.0
$Q_{cool,tot}$	kWh	125.7	492.4	611.3	620.0	626.1	628.5
$E_{el,cool,tot}$	kWh	17.4	100.9	36.0	40.3	44.8	49.1
EER_{sys}		7.2	4.9	17.0	15.4	14.0	12.8
E_{PV}	kWh	743.1	743.1	775.3	775.3	775.3	775.3
$E_{el,surplus}$	kWh	725.7	642.2	739.3	735.0	730.5	726.2
$E_{el,VC}$	kWh	17.4	10.2				
$Q_{cool,VC}$	kWh	125.7	62.2				
$E_{el,CH}$	kWh		90.7		8.1	18.7	31.6
$Q_{cool,CH}$	kWh		430.2		59.7	144.0	257.3
$E_{el,FC}$	kWh			36.0	32.3	26.1	17.5
$Q_{cool,FC}$	kWh			611.3	560.3	482.1	371.2

Table 3: Comparison of cooling systems

Figure 3 shows the average daily room temperatures for the conventional cooling, CoolShift without the chiller and CoolShift with $P_{switch} = 1000$ W as well as the average room temperature band. All temperatures increase at 8:00 and decrease at 17:00 by about 1.5 K because of the internal load. With the conventional cooling, the room temperature dips after midnight because the nocturnal ventilation is switched on. The room temperature peaks around 10:00, before the switch-on threshold of the chiller is reached. The slight increases in room temperature after 6:00 and 17:00 are caused by residual heat from the building mass. CoolShift slowly lowers the temperature during the night. During the day, the internal load causes a slow but consistent temperature rise. Since CoolShift directly cools the building mass, no residual heat effects occur.
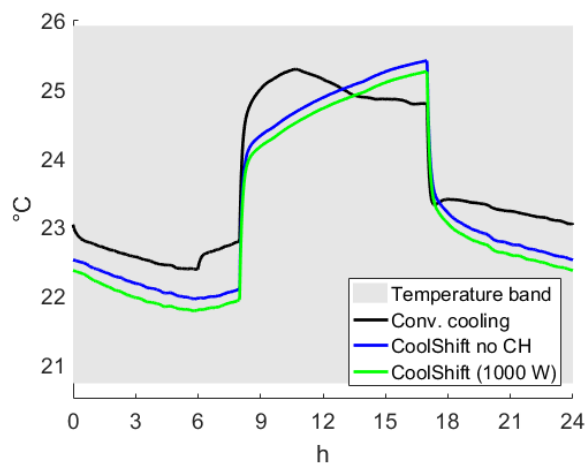

Figure 3: Average daily room temperature profiles and limits

4. Discussion & Conclusions

For the given building, HVAC components and climate, the electricity consumption of CoolShift is between 51 % and 64 % lower compared to the conventional cooling system. However, CoolShift occasionally exceeds the room temperature band. Naturally, the room temperature cannot be controlled during the day and slowly rises from morning to evening. It is shown that a TABS ceiling provides sufficient thermal storage to cover the delay between cooling supply and demand. For retrofits, combining ceiling panels with thermal storage is an alternative. Due to the constant internal loads, the daily temperature rise is rather constant, which made it possible to mostly avoid over- or under-cooling with a simple control strategy. In reality, the internal load can fluctuate considerably, which could be partially compensated with a learning controller. Noteworthy are the high ratios of free cooling to chiller cooling for the CoolShift variants. As an added benefit, the passive cooling by the heat exchanger at the backside of the PVT collectors increases the PV yield by 4.3 % by cooling the solar cells, even without fluid circulation.

5. Outlook

The presented work is a preliminary study. A larger follow-up project may include additional optimization and validation. The thermal activation of the building mass can be extended by placing the pipes deeper inside the ceiling or by activating the walls and the floor. To enable temperature control during the day, a dedicated storage tank may be added. Water or a suitable phase-change material may be used as storage medium. Considering the nature of the proposed cooling system, predictive control using weather forecasts may result in improved performance.

Since the PVT panels are used in a way they are not designed or tested for, their thermal properties should be experimentally validated under corresponding conditions. Furthermore, the modeling of the chiller is highly idealized and should be replaced with a model based on test data, once an appropriate product is selected.

While PVT collectors are designed to supply heat during daytime operation, only the cooling case is evaluated in this study. An extension including regeneration of seasonal storages and space heating during the cold months should be considered. Similar to the nocturnal cooling case, PVT collectors cannot always supply sufficient heating temperatures on their own and should be used in combination with a heat pump. However, a significant degree of free heating may be possible, especially during spring.

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Appendix

The following tables contain specifications of the building and HVAC components. The full parameter set is out of scope for this paper.

Room	
Room length south	8.82 m
Room length west	4.92 m
Room height	2.61 m
Window area south	11.75 m²
Window area west	6.55 m²

Internal walls	
Plaster	1 cm
Drywall	2.5 cm
Insulation	10 cm
Drywall	2.5 cm
Plaster	1 cm

Chiller, CoolShift	
Compressor power	120-400 W
Carnot efficiency	40%
ΔT condenser	2 K
ΔT evaporator	2 K

PVT collectors	
Area	4 * 1.98 m²
Supply piping (d * L)	2 cm * 20 m
Mass flow	0.25 kg/s
P_{el} circulation pump	35 W

TABS ceiling	
Area	43 m²
Depth of pipes	5 cm
Supply piping (d * L)	2 cm * 20 m
Mass flow	0.3 kg/s
P_{el} circulation pump	35 W

Windows and external walls (inside to outside)	
Glass layers	3
U value	0.9 W/m²K
G value	0.43
Plaster	1 cm
Concrete	20 cm
Insulation	24 cm
Plaster	2 cm

Floor and ceiling (top to bottom)	
Flooring	1 cm
Concrete	8 cm
Acoustic damper	2 cm
Insulation	3 cm
Concrete	28 cm

Chiller, conventional cooling	
Compressor power	120-400 W
Carnot efficiency	40%
ΔT condenser	7 K
ΔT evaporator	2 K

Air-side fan	
Mass flow	0.16 kg/s
P_{el}	15 W

Ceiling panels	
Area	12 * 2.05 m²
Supply piping (d * L)	2 cm * 20 m
Mass flow	0.3 kg/s
P_{el} circulation pump	35 W