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Energy efficient building cooling by combining a regenerative cooling system, a large TES and a phase change material cooling ceiling

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Abstract

The Würzburg division of the Bavarian Center for Applied Energy Research (ZAE Bayern) moved into its newly-built research building, the Energy Efficiency Center, upon its completion in 2013. It is a highly innovative building and was designed as a living lab. The cooling system is highly efficient, incorporating a combination of Passive Infrared Night Cooling (PINC), thermal energy storage (TES) and newly-developed ceiling cooling elements with integrated phase change materials (PCM). The PINC system can achieve high energy efficiency ratios (EER) of approx. 10-20. The PCM in the cooling ceiling provides passive cooling during the daytime in the transition period. Active cooling is only required in summer. In practice, the large-scale thermal energy storage tank has provided cooling for periods even up to ten weeks. This paper presents the first results of the combined system (PINC, TES, and cooling ceiling) as well as some of the measures undertaken to optimize it, and ideas for further improvement.

Keywords: *passive infrared night cooling (PINC), phase change material (PCM), cooling ceiling, High-Level-Controller, thermal energy storage, energy efficiency ratio, monitoring*

1. Introduction

In 2010, a project was launched by the Energy Efficiency division of ZAE Bayern in Würzburg to design, finance and build a new headquarters for the expanding institute. This new building, the "Energy Efficiency Center" (EEC), incorporates the cutting-edge and energy-efficient building technologies, mainly developed by ZAE Bayern itself, and present information about their relevance and impact in an information center open to the public. This is described in details in Weismann et al. (2014). Not only are the current new technologies and systems used in the building monitored and improved, but the modular design of the structure enables experimental components and systems to be integrated into the building for testing and further development.

ZAE Bayern moved into the building in June 2013. The building automation system was gradually put into operation, initial improvements being made in the areas of heating, ventilation, cooling and, according to Reim (2016) in lighting as well.. The Energy Efficiency Center is being extensively monitoring within the framework of a project (MoniResearch).

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Fig. 1: South-west view of the Energy Efficiency Center in Würzburg. © ZAE Bayern, photo by Petra Höglmeier.

2. Cooling Concept

2.1 Passive Infrared Night Cooling

Building directives stipulated that the EEC needed two underground fire protection water tanks with a volume of 100 m^3 each. It was decided to additionally utilize them for cold water thermal energy storage. They are both connected to the building's water cooling circuits by means of heat exchangers.

Fig. 2: Underground fire protection water tank.

One tank is cooled by a conventional compression cooler (and used as a backup for PINC), the other is connected to the passive infrared night cooling system developed by ZAE Bayern. A schematic diagram of this system can be found in Fig. 3, more details are described in Rampp et al. (2013).

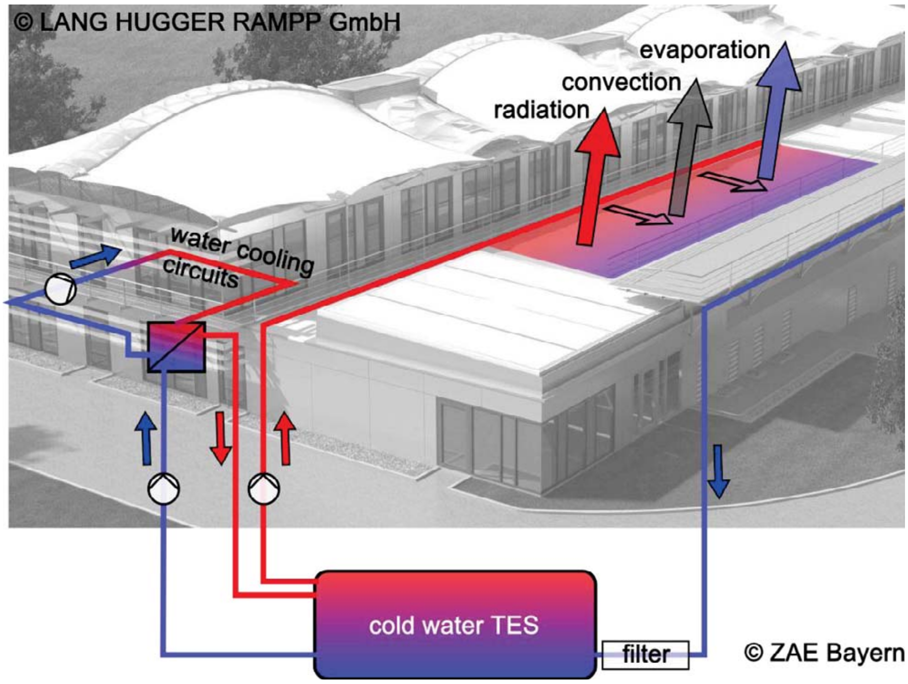

Fig. 3: The cooling load is connected to the TES by means of a heat exchanger. The water in the open circuit is re-cooled via infrared radiation, convection and evaporation when distributed over the surface of the roof when the temperature is sufficiently low (mainly at night).

Heat from cooling appliances in the laboratories and the PCM cooling ceilings in the offices is transferred into the TES by means of a heat exchanger. In order to re-cool the TES, the water is pumped onto the metal-sheeted area of the roof. Since it is a hydraulically open system, the water runs freely over the slightly sloped rooftop surface and ideally cools down to just under dew-point temperature. Heat is released via radiation exchange with the cold night sky, convection, as well as evaporation. The cooling power density is:

$$\dot{q} = \dot{q}_{rad} + \dot{q}_{conv} + \dot{q}_{ev}, \qquad \text{(eq. 1)}$$

The main part of the cooling power density is apportioned to the radiation exchange with the night sky which is given by

$$\dot{q}_{rad} = \varepsilon_w \cdot (\sigma \cdot T_w^4 - G), \qquad \text{(eq. 2)}$$

where ε_w is the emissivity of water, σ the Boltzmann constant, T_w the water temperature and G the radiation density of the long-wave radiation from the sky given by

$$G = \sigma \cdot T_{sky}^4, \qquad \text{(eq. 3)}$$

with the effective sky temperature T_{sky}.

It is recognizable in eq. 2 that there is a strong dependence between the cooling power density and the water temperature. Thus higher water temperatures lead to a higher cooling power density. Assuming typical water temperatures of about 18°C and the climate conditions in Würzburg, a cooling power density of around 60 to 120 W/m^2 roof area can be achieved at night even in summer.

The cooled water flows through rain pipes, a filter, and collects back in the cold water TES. Electricity is only needed to pump the water, so a high energy efficiency ratio (EER) can be achieved. As PINC is an open system, water evaporates and the loss is balanced out by rain water.

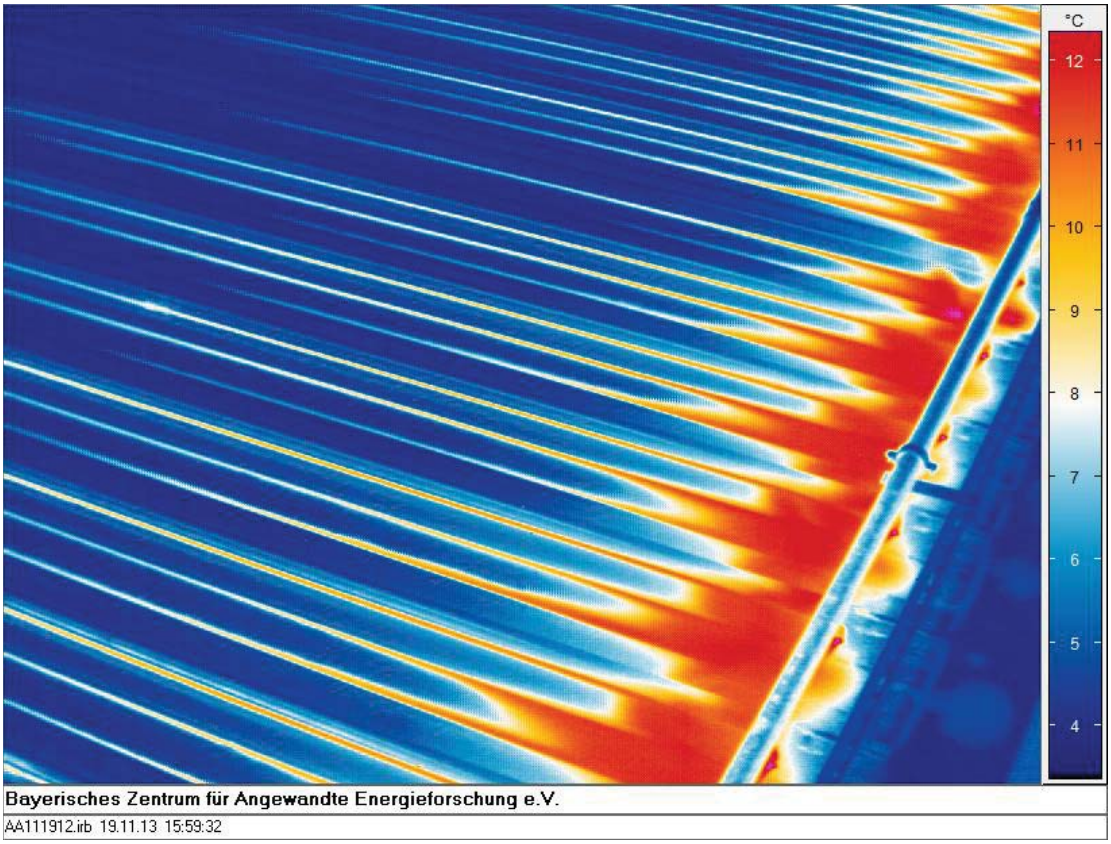

Fig. 3: Infrared image of the roof area used in the PINC system. On the right is the pipe which distributes the approx. 12 °C warm water over the roof surface. The water cools down over the roof to approx. 4 °C.

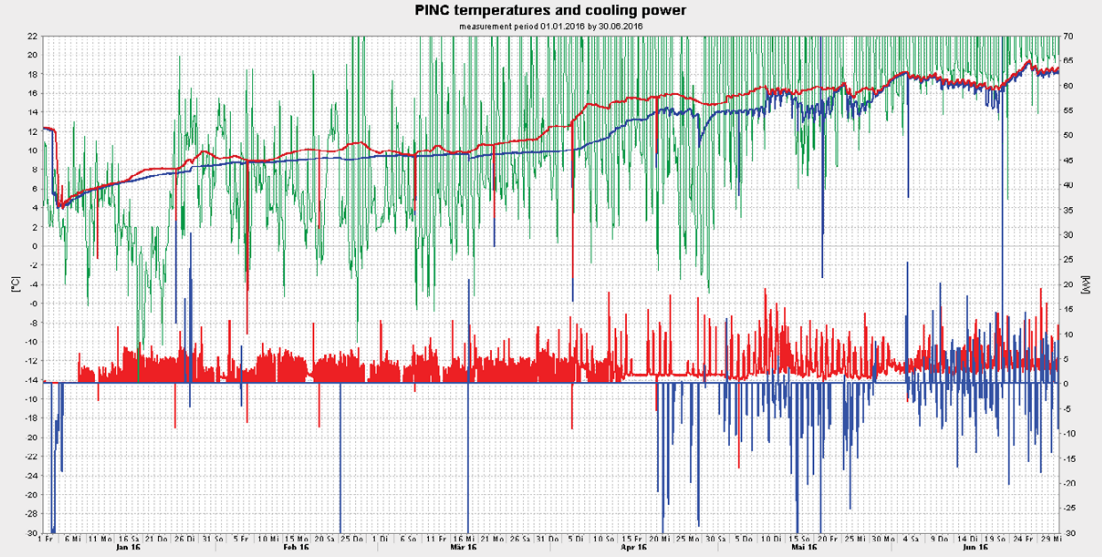

Fig. 4: PINC data from the first half of 2016. The red and blue plot lines in the top half show the temperatures in the TES, and the green represents the temperature on the metal roof. The bottom plot lines represent the cooling power (red = cooling required, blue = TES being cooled, right y-axis).

Fig. 4 shows the PINC data from the first half of 2016. Of particular note is the fact that right at the beginning of the year, on 03.01.2016, the PINC control system malfunctioned, causing the water in the TES to be cooled down from approx. 12°C to approx. 4°C within a couple of days. The frost failsafe mechanism then kicked in and turned the PINC off. The temperature unintentionally reached in the TES was so low that the PINC system was not needed to provide cooling until the middle of April 2016. When the TES is used to provide cooling, the temperature of the water in the tank increases. When it reaches 14°C, the PINC system is activated. The PINC's cooling power is typically between 8 kW and 16 kW for the 300 m² roof area, on clear, cold nights even higher.

An almost complete set of data was collected for 2015. The PINC system is compared here to a conventional compression cooling system that serves as a backup in the EEC (a DYNACIAT LG/LGP 240V R410A manufactured by Ciat with a net cooling capability of 69.2 kW). Recent (2017) investigations have shown that the backup system supports the PINC system at 29 % of the measured time steps in 2015 and in approx. 30 % of the time steps in 2016, which is more support than designed and estimated. Therefore the control of the PINC and the backup system actually is redesigned.

Nonetheless, from the measured data the EER of the PINC and the backup system can be determined. Tab. 1 shows an evaluation of the collected data.

Tab. 1: Data collected for PINC in 2015 shown in comparison to a conventional cooling system, with data also given separately for winter and summer.

	Whole year conventional	Whole year PINC	Winter conventional	Winter PINC	Summer conventional	Summer PINC
Generated cool / $kWh \cdot a^{-1}$	58570	21740	6080	6450	52490	15290
Electrical energy consumption / $kWh \cdot a^{-1}$	16545	1102	975	157	15570	945
EER /	3,54	19,73	6,24	41,08	3,37	16,18

If the cooling generated for the whole year by the conventional system and PINC are compared (each measured directly at the cooling unit, not taking the heat exchanger and pumps into consideration), it can be seen that the conventional system produced considerably more cooling. The PINC's EER, however, is more than 5 times higher than that of the conventional system. The difference is even greater when comparing the data for winter: the PINC's EER of 41.08 is even 6 times higher than that of the conventional system. Winter is defined here as the period from November to March. During the remaining period (summer), the PINC's EER of 16.18 is still considerably higher than that of the conventional system (3.37).

If the additional energy consumption caused by pumps, valves and heat exchanger connecting the cooling systems to the TES are taken into consideration when calculating the EER, the conventional system has an EER of 1.95 and PINC has an EER of 10.66 (whole year each). The pump regulation system for the heat exchanger is, however, still a little bit faulty and requires optimization.

2.2 Cooling ceiling with integrated phase change material

Heating/cooling ceilings were installed in the upstairs offices of the EEC to utilize the cold generated by the PINC for energy-efficient building temperature control. These cooling ceilings were built by Lindner AG based on their cooling ceiling Plafotherm-E 200, and specially modified to incorporate PCM. 20 offices have cooling ceilings with macroencapsulated PCM modules on top of the water pipes (PCM on top), and 3 offices have cooling ceilings with the PCM modules attached underneath the water pipes (PCM at the bottom). Figure 5 shows the two different cooling ceilings. A graphite layer is used to improve the thermal contact between PCM, water pipes and the cooling ceiling surface.

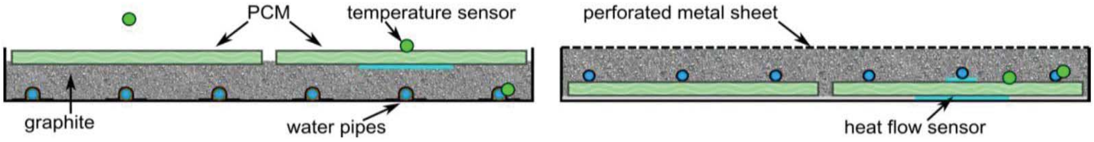

Fig. 5: Schematic diagram of the two PCM cooling ceiling systems "PCM on top" (ceiling type 1 on the left) and "PCM at the bottom" (ceiling type 2 on the right). The additional sensors are also indicated.

The PCM modules in both ceiling types are produced by Rubitherm Technologies GmbH. The metal cases contain a salt-hydrate-based PCM with a melting range between 22 °C and 24 °C. Five PCM modules are attached to one ceiling panel as shown in Figure 6.

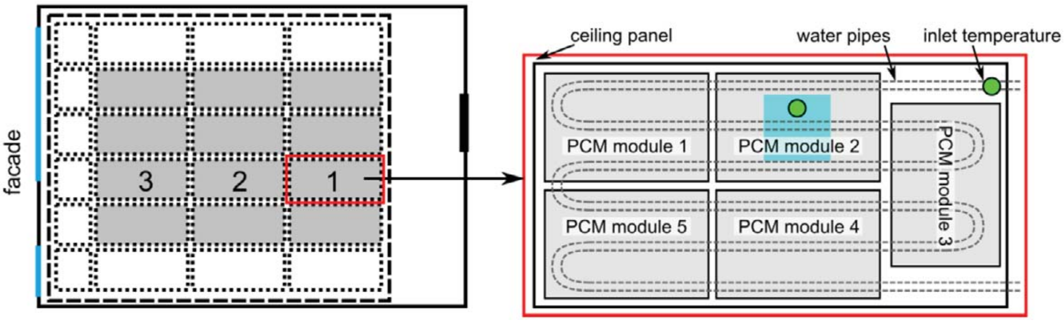

Fig. 6: Schematic diagram of the cooling ceiling panel arrangement in the offices (left) and the placement of the PCM modules on a single ceiling panel (right). The blue square indicates the position of the heat flow sensor.

The two different ceiling constructions were designed to enhance different operation modes of the ceiling. The operation modes are defined as follows:

- Passive cooling mode (PC mode):

  PC mode (no water flowing through the ceiling) occurs, if the system is not in one of the other operation modes mentioned below, and if the PCM temperature is below the operative room temperature.

- Active cooling mode (AC mode):

  AC mode occurs during the daytime, if the room temperature exceeds the set cooling temperature and the passive cooling power of the PCM is not sufficient. In AC mode, cold water flows through the ceiling.

- Active regeneration mode (AR mode):

  AR mode does the same as AC mode, but at night, thereby ensuring PCM regeneration.

The cooling circuit is connected to the PINC's TES by means of a heat exchanger. The standard room temperature is set at 24 °C, but this can be adjusted by the user by ±3 °C. Ceiling type 1 (PCM on top) was designed for balanced performance in every operation mode. This system performs well in AC mode as the water pipes have direct thermal contact to the ceiling panel, but also in AR and PC modes as the PCM has good thermal contact with the pipes and the ceiling surface via the graphite layer.

The design of ceiling type 2 (PCM at the bottom) is targeted towards PC mode. In PC mode, the system benefits from the direct contact of the PCM modules with the cooling ceiling surface. In AR mode, the system also shows decent results as the cold water in the pipes is not heated up by the room temperature while the PCM is regenerating. However, in ceiling type 2, the PCM acts as thermal resistance, meaning the room temperature cannot be regulated as well in AC mode.

Data on the cooling ceilings' performance was collected at the weekend when the building was not occupied. To minimize the influence of factors which are hard to quantify (such as solar gains), the outside blinds were closed during the whole measurements. The internal heat gains in the rooms were replicated using electrical heating devices designed to emit the heat equally via radiation and convection. The heating devices could produce heating powers between 350 W and 1000 W which correspond to specific heat loads between 16 and 46 W/m² floor area. During typical measurement days the heating devices were turned on between 7 am and 8 pm. Weinläder et al. (2016) has found that the passive cooling power $P_{t,PCM}$ of the two PCM ceiling types was a function of the specific heat load as well as the room globe temperature . For a globe temperature of 26 °C typical passive cooling powers range from 10 to 15 W/m² (Figure 7). For these measurements the cooling set point of the room temperature was increased from 24 °C to 26 °C. This allowed globe temperatures of up to 27 °C before the active cooling mode started.

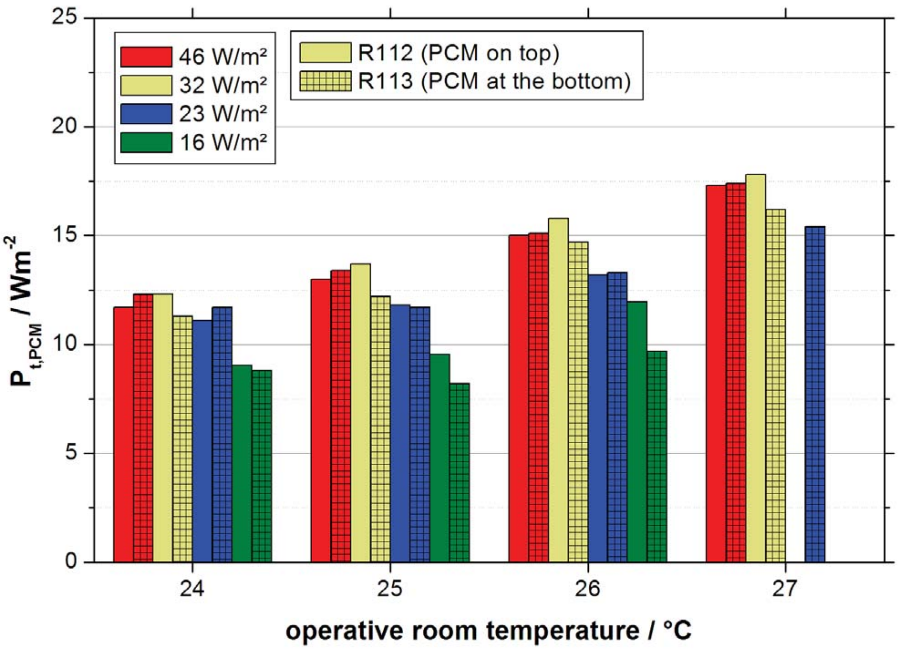

Fig. 7: Mean total passive cooling power $P_{t,PCM}$ of the PCM cooling ceilings as a function of operative room temperature for the different specific heat loads. No data are available in some cases for operative room temperatures of 27°C and for low specific heat loads.

The energy needed for active cooling was also measured during these weekends. The measurements took place in four office rooms with different systems as shown in Table 1. In addition to the PCM cooling ceilings all of the rooms except the reference room are equipped with PCM wallboards. For the sake of completeness further research results of passive PCM systems can be found at Kalnaes and Jelle (2015), Pomianowski (2012) and at Zhou et al. (2016).

Tab. 1: Overview of the different setups in the four measurement rooms.

room number and description	setup
R110: reference room	conventional cooling ceiling + conventional wallboards
R111: PCM on top + Energainboard	PCM cooling ceiling (PCM on top) + DuPont PCM wallboards (Energain)
R112: PCM on top + Comfortboard	PCM cooling ceiling (PCM on top) + Knauf PCM wallboards

	(Comfortboard)
R113: PCM at the bottom + Comfortboard	PCM cooling ceiling (PCM at the bottom) + Knauf PCM wallboards (Comfortboard)

The control during the day was the same for all four rooms, which means that the cooling set point for active cooling was 26 °C. During the night between 10 pm and 6 am the active regeneration mode was on in all the PCM rooms (R111-R113) but not the reference room. The cooling energy for active cooling was measured with a cold flow meter that detects the volume flow as well as the inlet and outlet temperature. The cooling energy is depicted in Figure 8 for the two periods during working hours (between 8 am and 6 pm) and outside working hours (from 0 to 8 am and 6 to 12 pm). The PCM passive cooling power was measured with heat flux sensors. The signal of the heat flux sensors was taken only during the working hours and only when the active cooling was turned off. The results for two measurement weekends (four days) during the summer with specific heat loads of 46 W/m² are depicted in Figure 8.

While the reference room has high cooling energy consumption during the daily working hours, the PCM systems reduce the active cooling energy during the day by 40 % to 80 %. This is achieved by their passive cooling potential (green bars in Figure 8). During the night, the rooms with the PCM systems require more cooling energy due to the regeneration process of the PCM (blue bars in Figure 8). This yields to a higher total amount of active cooling energy (sum of red and blue bars in Figure 8) in R111 and R112 compared to the reference room R110 while the total active cooling energy in R113 is slightly lower than that of R110.

It must be noted, that the PCM systems in R111 and R112 which had a higher total energy consumption could achieve mean globe temperatures during the working hours of about 1 °C lower than the reference room (temperature values in white areas in Figure 8). Even the PCM system in R113 which needed less cooling energy than the reference room achieved mean globe temperatures that were about 0.5 °C lower than that in R110.

The measurement results can be summarized as follows:

- PCM systems can shift a big portion of the daily cooling loads to the night
- PCM systems need a lot of energy for cooling down due to the nightly PCM-regeneration; this could lead to higher total cooling energy consumption than for a conventional cooling ceiling, depending on PCM system
- the PCM system in room R113 (PCM cooling ceiling with PCM at the bottom + Knauf PCM wallboards) is slightly advantageous compared to a conventional cooling ceiling with respect to the total energy consumption
- the efficiency of the cold production during the night is highly important for the investigated PCM systems
- since cold usually can be produced more efficiently during the night due to lower ambient temperatures, even the PCM systems in R111 and R112 with a higher total cooling energy consumption might be advantageous compared to a conventional cooling ceiling
- the PCM systems improve thermal comfort (lower mean globe temperatures) compared to the reference room at the same control parameters. Due to the time shift to the night, even with a much smaller TES the cooling energy in this case can be produced more efficient.

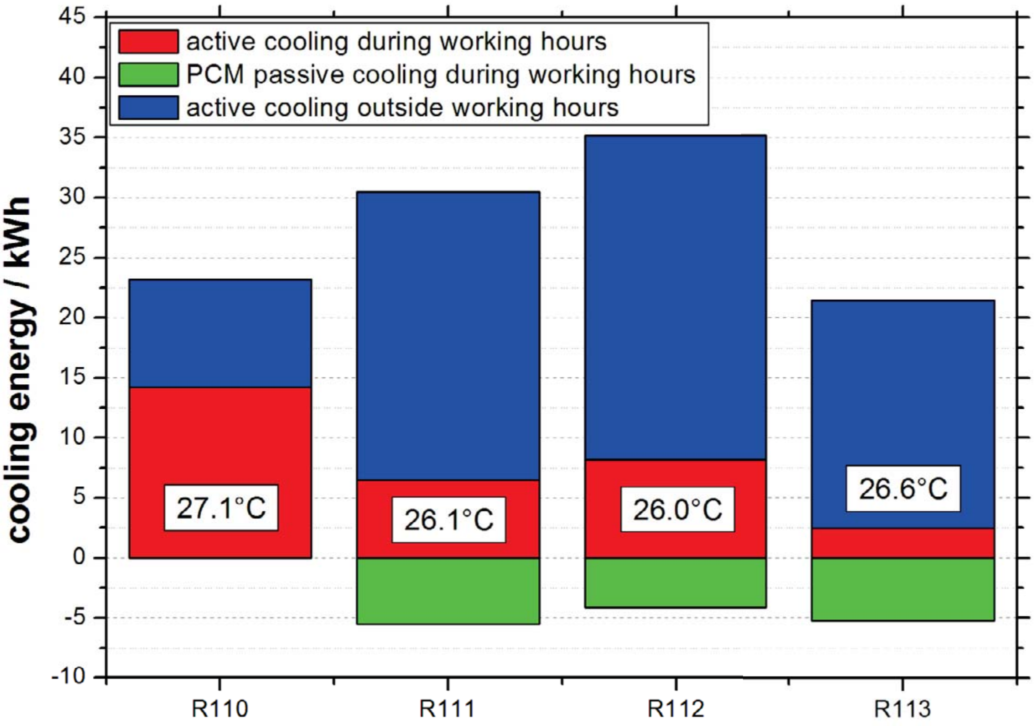

Fig. 8: Active and passive cooling energy of the cooling ceilings in four office rooms with specific heat loads of 46 W/m² between 7 am and 8 pm. The values in the white areas depict the mean globe temperature during the working hours.

3. Improvements and Outlook

A new water distribution method was introduced to increase the efficiency of the PINC system. The water is now distributed over the roof through a pipe with slits instead of nozzles, with hardly any loss in pressure.

The cooling circuits in the EEC are going to be restructured so that the PINC system can also be used in winter.

Furthermore, work is being carried out on developing the PINC's control system. Instead of using fixed trigger criteria, a high-level controller which factors in the weather forecast as well as cooling load prognoses calculated by means of building simulation enabling optimum control could improve the performance of the PINC. Simulations of the improved control system have shown an increase in efficiency of approx. 30% of the EER.

The conventional compression cooling unit (for backup purpose) is connected to ab big TES as well. For higher efficiency it is planned, to operate this cooling unit only at night time. At daytime, the TES should have sufficient cold stored for the cooling load of the EEC as shown at Gwerder and Illi (2016).

The PCM systems as well as two cold production systems (PINC + conventional compression chiller) will be implemented into a TRNSYS model that will be validated with the monitoring data. The models then will be used to investigate the performance of the PCM systems including cold production.

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