Thermally Activated Building Systems Using Phase-Change-Materials

D. Kalz[*], J. Pfafferott, P. Schossig and S. Herkel
[1] Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, D-79110 Freiburg, Germany
[*] Corresponding Author, email: doreen.kalz@ise.fraunhofer.de

Abstract

This paper outlines the effects, the potential and the performance of thermally activated building systems (TABS), as well as an evaluating comparison with an all-air conditioning system by means of a validated building and plant model in ESP-r. Preliminary experiments in a commonly operated room of a low-energy office building facilitate the calibration of the simulation model. In particular, the simulation study was carried out for (i) concrete core conditioning, (ii) grid conditioning without and (iii) with 20% of micro-encapsulated PCMs applied to the ceiling. The central conclusions of this study are: (1) Grid conditioning provides a satisfactory room performance comparable with concrete core conditioning, (2) the application of PCMs contributes to a reduced operative room temperature, and (3) PCM with a melting range of 21 to 24 °C is most favourable throughout all applications.

Keywords: Thermally Activated Building Systems (TABS), Phase Change Materials (PCMs), Simulation.

1. Introduction

One approach to condition low-energy office buildings in summer employs the utilization of the building's thermal storage activated by low exergy heat sinks (i.e ambient air, ground water, soil) which operate with small temperature differences to the room temperature [1]. Extensive research has been surveyed on passive building thermal storage utilization, e.g. the precooling of a building's thermal mass during night time in order to shift and reduce peak cooling loads in commercial buildings, as well as energy consumption [2, 3, 4]. During the last decade the thermal activation of building components by water driven systems (TABS) have been gaining an increasing market as promising technologies in reducing energy consumption and improving occupant thermal comfort [5, 6, 7]. Unlike all-air systems, radiant cooling systems by TABS condition the space through a combination of natural convection and radiation insight the building.

Basically, all TABS have in common, that pipes are incorporated directly in the surface of the building or in panels which are suspended on the ceiling. The TABS examined in this study on the basis of a validated building and plant model in the simulation environment ESP-r [5] are (i) concrete core conditioning, (ii) grid conditioning without and (iii) with the application of 20% micro-encapsulated PCM in varying melting ranges 21 - 24 °C, 22 - 25 °C and 23 - 26 °C.

This article outlines the effects, the potential and the performance of concrete core conditioning versus grid conditioning, as well as an evaluating comparison with an all-air conditioning system with respect to thermal comfort and cooling capacity. The following questions will be addressed:

1. Which room performance can be achieved with different cooling strategies?
2. Does grid conditioning as to concrete core conditioning provides a comparable cooling capacity?
3. Does grid conditioning in combination with PCM have an advantage over grid conditioning only?
4. Which is the most favourable melting range of the PCMs?

2. Test facility

2.1 Description of the test facility

To investigate the potential of thermally activated building systems, the Fraunhofer SOBIC [www.sobic.fraunhofer.de] in Freiburg, Germany is used as the experimental test facility (Table 1). Concrete core conditioning [Fig. 1] is installed in the ceiling of the office area. The HVAC system consists of an air-handling system and a cooling tower which operates as the heat sink, as well as pumps and auxiliary equipment needed to provide cooling. Besides, extensive instrumentation is available to monitor the operational characteristics of the cooling plant including the thermally activated building component (ceiling) and the thermal performance of the rooms.

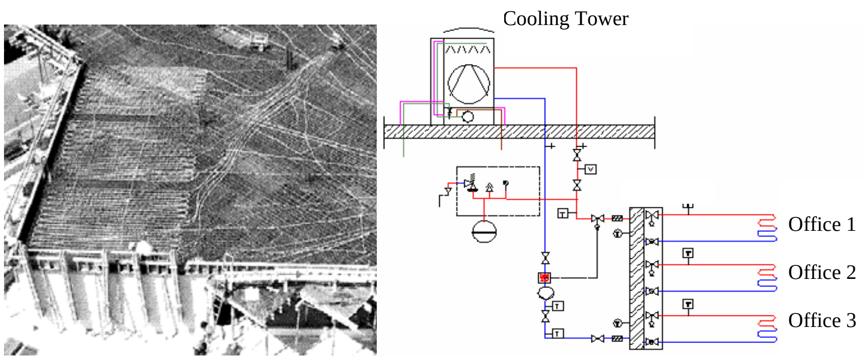

Fig.1 Concrete core conditioning for three offices in the Fraunhofer SOBIC (Germany) before concreting (left). System schematic of concrete core conditioning of the ceiling with cooling tower as heat sink (right).

Table 1 Building characteristic. The unconditioned building in the period 22.08 – 27.08.04 is characterised by its heat gains, temperature amplitudes, the heat loss coefficient and the storage capacity. The values are related to the exterior wall (EW) (Table 1) [9].

Table 2 Physical properties of gypsum plaster containing 20 % of micro-encapsulated PCM.

Table 1: Building characteristics.	
Heat gain G_m [W/m$^2_{EW}$]	23,7
Heat gain ΔG [W/m$^2_{EW}$]	36,9
Heat loss coefficient H [W/(m$^2_{EW}$K)]	1,9
Storage capacity C [Wh/(/(m$^2_{EW}$K)]	105,0

Table 2: Physical properties of PCM.	
Material	Paraffin
Density [kg/m³]	860,0
Thermal conductivity [W/(mK)]	0,2
Amount of PCM [kg/m²]	2,6
Sensible specific heat [J/(kgK)]	1.000,0
Latent heat fusion [J/kg]	18.000,0
Melting range [K]	3,0

2.2 Experiments with concrete core conditioning

The experiments were conducted under typical operation conditions in an unfurnished and unoccupied test office (floor area 20 m², room height 3,10 m) with a true north/south solar alignment during the months of August and September 2004 (Figure 2). False internal heat gains of 55 W/m² were introduced using baseboard heaters (90% convective and 10% radiative heat gain) to simulate the occupancy schedule of a typical commercial office building (8 am to 4 pm). The solar shading (internal Venetian blinds) is lowered during the entire experimental period resulting in a *g*-value of 0,42. Concrete core conditioning operates with a flow rate of 24 l/(m²h) during 10 pm and 6 am and the air handling system supplies the office during workdays from

7 am to 5 pm. The defined interior heat gains dominate together with the concrete core conditioning the energy balance of the office compared to solar radiation, infiltration and transmission heat losses to adjacent rooms and, hence, simplify the model-based analysis of the TABS.

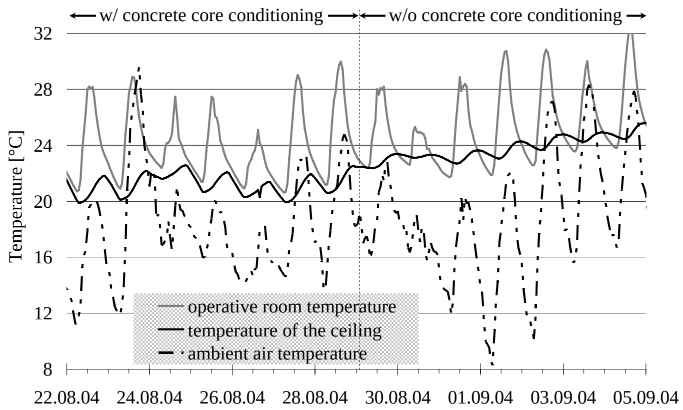

Fig. 2 Measurements from long term monitoring with and without the operation of concrete core conditioning. As expected, the temperature of the activated ceiling (average performance of 20 W/m²) fluctuates stronger during the operation of the concrete core conditioning, and the operative room temperature tends to increase without a room conditioning.

3. Validated building and plant model in ESP-r

Preliminary experiments (Fig. 2) facilitate the calibration of the simulation model with respect to the building thermal response, the plant system, and the operation schedule. Since the simulation calculates the room dry bulb temperature, the improved heat transfer from the activated building component to the air has to be considered explicitly in the model: Convective heat transfer coefficient for ventilation α_{NV}= 4 W/(m²K) and for core concrete conditioning α_{Tab}= 12 W/(m²K). As supported by Fig. 3, measured and modelled values for the building room temperature and the plant fluid temperatures are in good agreement.

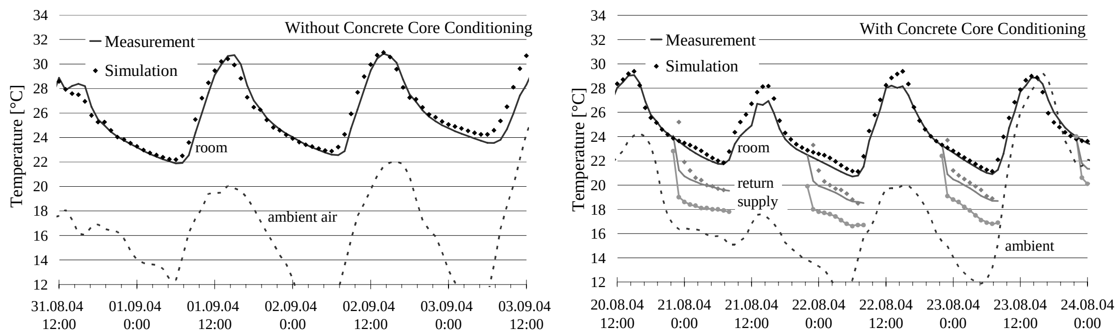

Fig. 3 Validated building and plant model (slab embedded systems in ESP-r) for the operation without (left) and with (right) concrete core conditioning on the basis of experimental measurements.

4. Simulation study of thermally activated building components for cooling purposes

The presented simulation study is carried out for the period 22nd to 27th of August 2004. It should be emphasized that the building with its thermal history is found in a highly dynamic period, and thus the results are applied to this specific time window.

4.1 Heavyweight construction

The validated building model (Fig. 3) is used for further analyses of the introduced cooling strategies. Therefore boundary conditions were generalized according to a typical operation of office buildings (144 Wh/(m²d)). Since the study focus on the thermal behaviour of the room and not on the cooling plant, measured values are taken from the previous experiment. This implies given constraints: Measured water supply temperatures are applied to the simulation and algorithms which control the temperature or the flow rate of the chilled water are not taken into account.

(i) Concrete core conditioning according to the experiment: Pipes (diameter of 20 mm, spacing 150 mm) embedded in the concrete layer of the ceiling, operation from 10 pm to 6 am, and flow rate of 24 l/(m²h).

(ii) Grid conditioning: Ceiling suspended capillary pipes (diameter 3,4 mm, spacing 15 mm, area 10 m²) imbedded in 15mm gypsum plaster, operation from 10 pm to 6 am, and constant flow rate of 6 l/(m²h) in order to avoid thermal discomfort at the beginning of occupancy.

(iii) Grid conditioning combined with PCMs : Like before (ii), but gypsum plaster contains 20% of micro-encapsulated PCMs (by weight). Varying melting ranges of the PCMs (21 – 24 °C, 22 – 25 °C and 23 – 26 °C) are examined (Table 2).

These strategies are compared to cooling through night ventilation (NV) with a common ACH of 4 and to the unconditioned office room (Fig. 4 and 5).

Conclusion:

- If the office does not get conditioned, the average operative room temperature results in 31 °C with an amplitude of 4,7 K.
- Night ventilation with 4 ACH reduces the average temperature by 5 K and the peak temperature by 4 K.
- Concrete core conditioning results in a good room performance (average operative room temperature of 22,7 °C) and significantly lower daily temperature amplitudes, since it makes best use of the thermal mass of the construction.
- Compared to concrete core conditioning, ceiling suspended capillary pipes with an flow rate of 6 l/(m²h) lead to an increased operative room temperature of 0.8 K. However, peak room temperatures are higher, since the grid conditioning cannot activate the building mass to its full extend.
- The microencapsulated PCM increases the thermal storage capacity of the construction and therefore favourably effects the development of the operative room temperature. This characteristic buffers the temperature increase. Besides, during the discharging and precooling period, the PCM hinders the room temperature to fall significantly.
- Finally, the differences of the room performance through a varying melting range of the PCMs are marginal. The lowest average room temperature is reached by PCM with a melting range between 21 and 24°C. However, the full potential of PCM to reduce the room temperature is not that distinctive since the office consists already of a heavyweight construction. The effects might be more visible in lightweight buildings where overheating during summer is a common problem. This will be investigated in the following section.

4.2 Lightweight construction

In the following the effects of grid conditioning in combination with PCMs are investigated in a lightweight construction, where as well as in retrofit purposes concrete core conditioning is not applicable. Again, the analysis bases on the same validated building model as in the previous study. Both, the characteristic of the exterior opaque surface and the operation of the office room remained unmodified. Solely the composition of the ceiling was changed towards a suspended ceiling which is poorly thermally coupled to the concrete layer of that surface. The following strategies are examined and compared to night ventilation and to the unconditioned office room:

(i) Passive PCM only: Micro-encapsulated PCMs (20%) with varying melting ranges are applied to a gypsum plaster. The PCM storage gets discharged by ventilating the room with an air change rate of 4 ACH during night time hours.

(ii) Grid conditioning

(iii) Grid conditioning with PCMs.

Conclusion:

- In the lightweight office operative room temperatures are higher throughout all applied cooling strategies compared to the heavyweight construction.
- For the night ventilation strategy with 4 ACH, the application of PCM with a melting range between 21 and 24 °C contributes to a decrease of the average operative room temperature of 0,8 K compared to the model without PCM.
- Grid conditioning results in a reduced average room temperature of 0,5 K compared to the strategy night ventilation in combination with PCMs.
- Figures 6 to 7 illustrate that actively discharged PCM by capillary tubes reduces the average peak temperature by 1.8 K compared to the strategy night ventilation in combination with PCMs and by 1,2 K compared to grid conditioning.
- Again, for an actively discharged PCM storage a melting range from 21 to 24°C turns out to be most favourable according to the average and to the peak operative room temperature.

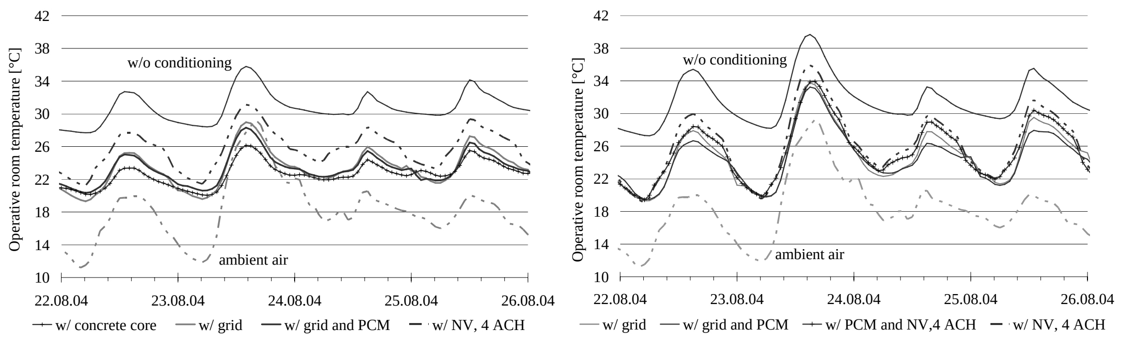

Fig. 4 Simulation study on the basis of the calibrated building model comparing several cooling strategies for a heavyweight building (left) and a lightweight building (right).

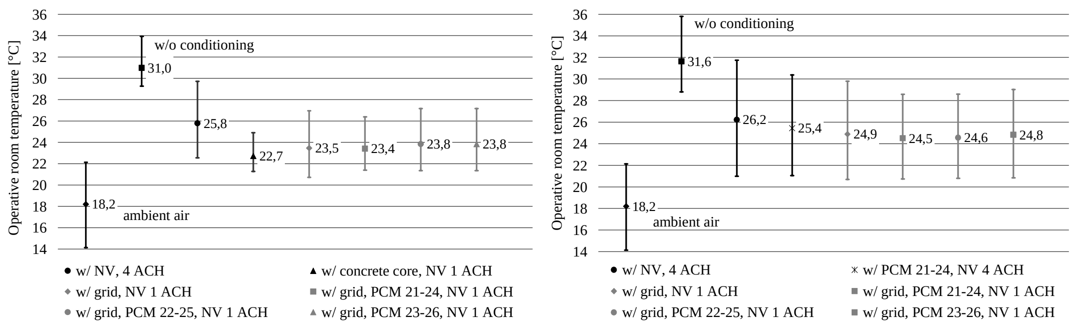

Fig. 5 Average operative room temperature (22nd to 27th of August) with an average daily amplitude (maximum and minimum), as well as ambient air temperature for several cooling strategies considering a heavyweight building (left) and a lightweight building (right).

5. Conclusion, Summary, and Future Work

The evaluation of the presented cooling strategies results in the following central conclusions:

- Cooling by ceiling suspended capillary tubes provides with a significantly reduced mass flow rate a satisfactory room performance comparable with concrete core conditioning. The cooling capacity by grid conditioning is just 12% lower than by concrete cooling, since the differences between supply and return water temperature are higher. Since according to [7] pressure drops within the grid conditioning system are small, a significantly increased COP can be expected.
- The application of PCMs contributes to a reduced operative room temperature. While relatively high ambient air temperatures considerably limit the modulating effect on temperature fluctuations through PCMs, an active discharge of the PCM storage through capillary tubes taps their full potential.
- When the PCM storage gets actively discharged by water driven TABS like capillary tubes, a melting range between 21 and 24 °C was found to be most favourable according to the average and the peak operative room temperatures.
- The study will be extended to long term operational periods including persistent heat waves and the findings through the simulation study should finally be supported by experiments in a controlled environment.
- A further step will compare the different cooling strategies according to their potential in saving energy consumption and decreasing the COPs while maintaining thermal comfort.
- Future work will investigate the potential and the performance of TABS in combination with PCM for the heating purpose.

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