MONITORING AND EVALUATION OF NIGHT-TIME VENTILATION AND RADIANT COOLING CONCEPTS APPLIED TO LOW ENERGY OFFICE BUILDINGS

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ABSTRACT

This article presents a simulation study comparing the thermal interior comfort performance, the energy consumption and the efficiency of (i) nighttime ventilation concepts considering varying air change rates, (ii) three thermo-active building systems (TABS) and (iii) ceiling mounted radiant cooling panels in a low energy office building for a chosen climate of the Test Reference Year (TRY) weather database as well as for the hot summer 2003 in South-West Germany. The investigation comprises the ambient air and the ground as low-exergy heat sinks.

The simulation study bases on a building and plant model within the simulation environment ESP-r which is validated by means of measurements derived from long-term monitoring in a low energy office building.

Keywords

Thermo-active building systems (TABS), Night-time ventilation, Natural heat sinks, Thermal comfort, Energy efficiency

INTRODUCTION

OBJECTIVES: This research study targets at analyzing and evaluating the cooling performance benefits of five low-exergy concepts for non-residential buildings employing the environment as heat sink. The objective is achieved through long-term monitoring and computer simulation of a representative low-energy office building in Germany, taking varying factors as energy delivery system, heat sink, operation mode, and climate into account. Due to a comprehensive result analysis, the introduction is limited to objectives and applied methodology.

ENERGY DELIVERY SYSTEM

(i) Mechanical nighttime ventilation with a varying hourly air change rate of 1, 2, 4, 6 and 8 conditions the building structure outside the time of occupancy if the operative room temperature exceed 22°C and if the ambient temperature is below the operative room temperatures. Free ventilation through windows often results in non-suitable operative room temperature even under normal German summer climate and, therefore, is not further discussed.

(ii) Concrete core conditioning and (iii) grid conditioning system, as well as (iv) ceiling mounted radiant cooling panels operate according to defined operation modes with varying water flow rates of 16 and 20 l/(m²h) employing a wet cooling tower and bore-hole heat exchangers (Figure 1, Table 1).

(v) Previous research (Kalz et al. 2007) demonstrates that latent heat storage materials in combination with a grid conditioning system can lower operative room temperatures during occupancy time. Therefore, a fifth approach considers 20% of micro-encapsulated phase change materials (PCM) which are integrated in the ceiling plaster and get discharged by a grid conditioning system operating under the afore given conditions. The present study considers a PCM melting range of 19 to 22°C.

In the following, the heat delivery systems are denoted as: concrete core conditioning (CCC), grid conditioning without (GRID) and with PCM (PCM), and radiant cooling panel (RCP).

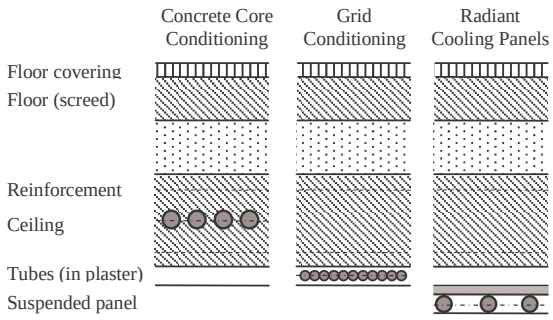

Figure 1 Construction element sections.

Table 1 Characteristics of the energy delivery systems.

	concrete core conditioning	radiant cooling panels	grid conditioning
heat sink	wet cooling tower and bore-hole heat exchangers		
flow rate [l/(m²h)]	16 and 20		
circuits	1	3	2
pipe diameter [mm]	20 / 18	14 / 12	5.8 / 4.3
pipe spacing [mm]	150	200	21
activated layer in component	concrete ceiling slab	aluminum panels	plaster

LOW-EXERGY HEAT SINK: Low energy non-residential buildings with a significantly reduced cooling demand allow for the utilization of natural high temperature heat sinks, such as the ambient air utilized by dry or wet cooling towers and the ground utilized by bore-hole heat exchangers.

WEATHER CONDITIONS: First, the study is carried out for a common German summer climate using the Test Reference Year (TRY) weather database 2004. In addition, the cooling potential and the limitations of the introduced cooling concepts are examined under the extreme summer conditions of 2003 as characteristic for a global warming scenario.

EVALUATION CRITERIA: The benefits and the cooling performance of the different cooling concepts are evaluated by the achieved thermal comfort performance, the end and primary energy demand as well as the energy efficiency.

DISCUSSED HYPOTHESIS: Interior thermal performance is significantly improved by a hydronic conditioning system compared to a nighttime ventilation concept, in particular, considering a global warming scenario.

(i) A grid conditioning system and ceiling mounted radiant cooling panels operate less efficient in a nighttime operation mode since they do not activate the building structure as effectively as a concrete core conditioning system.
(ii) The application of a concrete core conditioning system results in the best thermal comfort performance.
(iii) Integrated phase-change materials in the ceiling plaster activated by a grid conditioning system account for the reduction of maximum operative room temperatures, as though their effect is more prominent in lightweight constructions.
(iv) In daytime and continuous operation mode, the cooling performance of a grid conditioning system and radiant cooling panels is equivalent to the performance of a concrete core conditioning system.
(v) Utilizing the ground as heat sink harvest a higher cooling potential as against a wet cooling tower.

MODEL VALIDATION: At last, it is the purpose of this study to verify a building and plant model within the building simulation program ESP-r employing radiant systems served by natural heat sinks.

DEFINITION OF TERMS: Thermal comfort will be assessed using operative room temperature (ORT) and comfort classification according to the comfort criteria of ISO 7730 (DIN EN ISO 7730:2003-10) and of the Dutch guideline ISSO 74 (Boersta et al. 2005), which accounts for the thermal adaptation of the human being. ISO 7730 distinguish merely summer (ORT=24.5°C) and winter (ORT=22°C) cases. According to the Dutch ISSO 74, the comfortable room temperature responds to the running mean ambient air temperature of the last three days ATrm: ORT=17.8°C+0.31ATrm. The thermal comfort analysis is only carried out for the time of occupancy during workdays, not taken holidays or vacation into account.

The energy performance of the building is analyzed with respect to end and primary energy as defined by the umbrella document of the EPBD (CEN/BT EPBD 2006.) As though different for each country, the primary energy conversion factors for this study are selected to be 3.0 for electricity [DIN 18599]. Energy efficiency of cooling systems is defined as the cooling energy delivered to the space divided by the energy consumed by the cooling system, e.g., pumps and fans.

METHODOLOGY APPROACH

To investigate the relative energy and comfort merits of nighttime ventilation, thermo-active building components and radiant cooling panels, the following methodology is adopted:

(1) Long term monitoring over the course of one to three months of the introduced cooling concepts in a low energy office building (night ventilation, concrete core conditioning, radiant cooling panel) and in an experimental test bed (grid conditioning with and without PCM) in Freiburg, Southern Germany.
(2) Evaluation of the long-term measurements.
(3) Development of a building model of the low energy office building which served as the test facility as well as a flow network model for the ventilation concept and a plant model for the TABS and cooling panels in the dynamic building simulation environment ESP-r.
(4) Validation and calibration of the building and the plant model for all cooling concepts by means of measurements derived from the monitoring.
(5) Conducting simulation runs over the summer period of three month (June to August) for all cooling concepts.
(6) Evaluation of the results conducted by means of thermal comfort, energy consumption and energy efficiency analysis over the summer period.

DESCRIPTION OF TEST FACILITY

To investigate the potential of the previously introduced cooling concepts, three offices at the Fraunhofer SOBIC in Freiburg (48° north, 7.8° west) [www.sobic.fraunhofer.de], South-West Germany, are used as the experimental test facility. Concrete core conditioning is installed in the concrete slab and radiant cooling panels are mounted on the ceilings at 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 radiant cooling panels, as well as the thermal performance of the adjacent rooms and the ambient conditions.

MONITORING

Experiments were conducted in unfurnished and unoccupied test offices (floor area 20 m², room height 3.10 m) with a true north/south solar alignment during the months of June to September 2004, 2005 and 2006. According to the particular experiment, false internal heat gains of 15 to 55 W/m² were introduced to simulate the occupancy schedule of a typical commercial office building between 8 am to 6 pm. Solar shading - internal Venetian or external blinds - is installed in the offices resulting in an reduced g-value of 0.42, 0.22 or 0.11. Its operation varies according to the particular experimental set-up. The defined interior heat loads dominate together with the operation of the TABS and the radiant cooling panels, respectively, 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 radiant cooling systems.

VALIDATION OF BUILDING AND PLANT MODEL

To analyze the building energy performance for the introduced cooling concepts, a building and plant model in the simulation environment ESP-r are established. Preliminary experiments and measurements from the long-term monitoring facilitate the calibration of the simulation model with respect to the building thermal response, the plant system, and the operation schedule.

The following subchapters (I to V) outline in brief every experiment according to the cooling concept, as well as a comparison of relevant experimental measurements and simulated values (Figure 2 to Figure 3). Portrayed are the simulated and measured operative room temperature, ceiling surface temperature and the ambient air temperature for all experimental cases. For the radiant cooling concepts, the measured supply water temperature (which is applied to the simulation as input file), the measured and simulated water return temperature and the core temperature of the thermally activated building component are additionally illustrated in the figures.

Since the study focus on the thermal behavior of the room and the cooling performance of the energy delivery systems and not on modeling the heat sink, measured water supply temperatures and water flow rates are applied to the simulation, i.e., the cooling tower is not modeled as a single plant component.

In conclusion, simulation values agree well with the field measurements for the thermal performance of the room and plant. However, simulation results are sensitive to construction and plant parameters as well as to the calculation time steps per hour which should not exceed five minutes in order to prevent irregularities and deviances.

(I) FREE RUNNING MODE: During 8/30 to 9/6/2004 the chosen offices were left to react uninhibitedly (free float) with the adjacent zones and the exterior environment. They do not receive internal heat loads, but solar loads due to the open solar shading. Besides, the ventilation system was out of operation.

(II) NIGHT VENTILATION: During 5/25 to 6/13/2006 experiments with night time ventilation considering different air change rates and variable use of solar shading were conducted. For the illustrated period 6/9-6/5/2006, the office gets ventilated with a dynamic air change rates of 1 ACH between 7 am and 11 pm and 2.5 ACH between 11 pm and 7 am. Introduced internal loads during the assumed times of occupancy of 7 am to 5 pm amount to 15 W/m² and the lowered external solar shading results in a total g-value of 0.11.

(III) CONCRETE CORE CONDITIONING: During 8/20 to 8/29/2004 the concrete core conditioning system operates with a flow rate of 24 l/(m²h) during 10 pm and 6 am employing a wet cooling tower as heat sink. The air handling system supplies the office during workdays from 7 am to 5 pm with an ACH of 1. Introduced sensible loads during 8 am and 4 pm amount to 55 W/m² and 460 Wh/(m²d), respectively. The solar shading was lowered during the entire experimental period resulting in a g-value of 0.42. Moreover, the building with the applied cooling concept was validated using the simulation tool TRNSYS (Pfafferott et al. 2005). The simulated thermal performance agrees well with the results obtained by ESP-r.

(IV) RADIANT COOLING PANEL: During 8/15 to 9/4/2005 three radiant cooling panels were in operation between 10 pm and 6 am employing again a wet cooling tower as heat sink with an water flow rate of 19 l/(m²h). Varying internal heat loads of 17 to 34 W/m² and 340 to 680 Wh/(m²d), respectively, were introduced during 8 am and 6 pm. The ventilation system was not in use. External solar blinds reduce the total g-value to 0.22.

(V) GRID CONDITIONING WITHOUT PCM: During 7/24 to 8/8/2006 a grid conditioning system was operated with an flow rate of 33 l/(m²h) in an unoccupied and unfurnished experimental test bed which consists of two identical outdoor chambers (each 19 m²) in lightweight construction. The chambers have a glass façade orientated to south consisting of glazing with solar control coating resulting in a g-value of 0.34. Natural ventilation varies between air change rates of 0.2 to 1.5. Due to high solar load, the chambers do not receive additional internal loads.

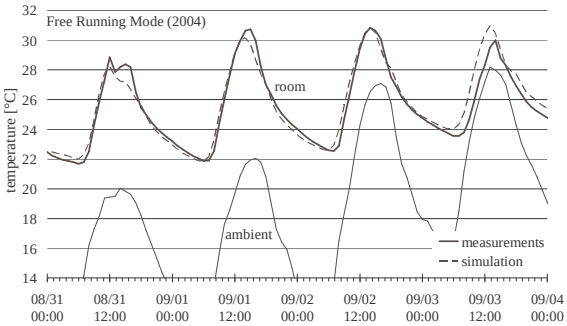

Figure 2 Free running mode (no ventilation, no cooling).

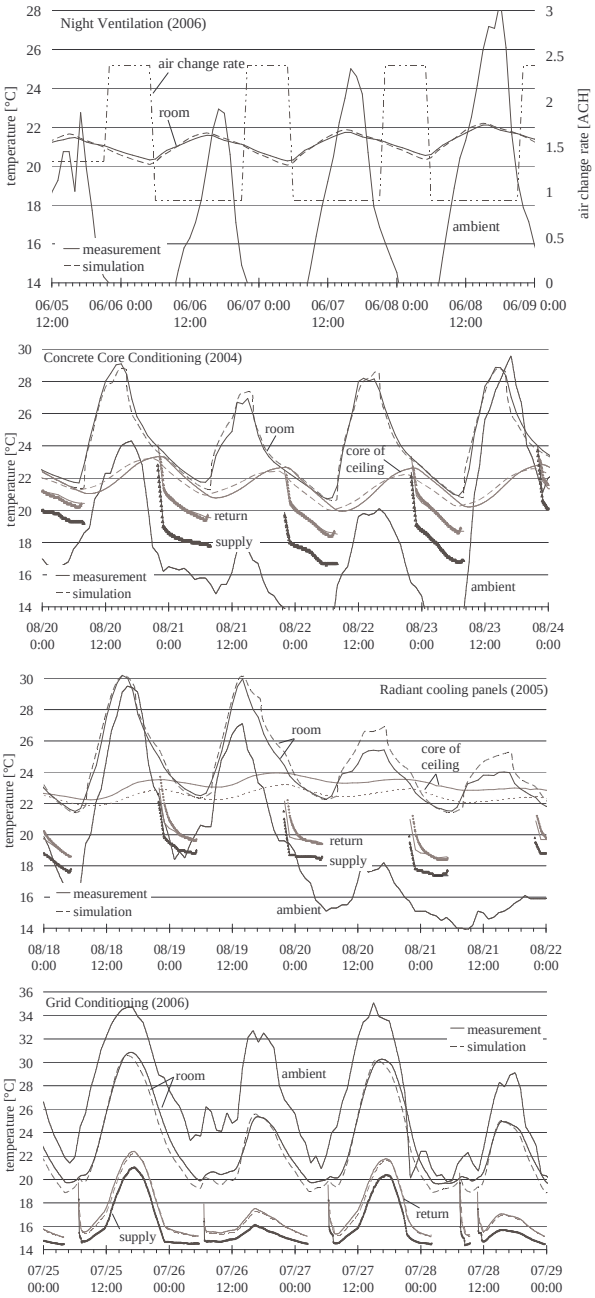

Figure 3 Comparison of measured (drawn though graphs) and simulated (dashed graphs) values for the following systems (top to bottom): night ventilation with 2.5 ACH, concrete core conditioning, radiant cooling panels and grid conditioning.

SIMULATION STUDY

The validated building and plant model is used for further analyses of the introduced cooling strategies. Therefore boundary conditions were generalized according to a typical operation of office buildings.

ESP-R MODEL: A *PCM model* (Heim and Clarke 2004) is integrated in the energy balancing of ESP-r (www.esru.strath.ac.uk/Programs/ESP-r) considering the effect of a phase change of latent heat storage materials by substituting the material characteristics which are assigned to a particular node within a multi-layer construction. The experimental verification of the PCM model in ESP-r was carried out by means of comprising measurements in a realistic experimental test bed (Schossig et al. 2003 and 2005). For describing a hydronic radiant energy delivery system, (Laouadi 2004) developed a detailed semi-analytical *plant model* which is used for modeling TABS systems. The model combines the one-dimensional numerical model of the energy simulation software with a two-dimensional analytical model.

WEATHER DATA: First, the Test Reference Year weather database for the location Freiburg characterized by an annual mean temperature of 10.4 °C is chosen for the study (denoted TRY12) (Figure 5, Table 2). In order to take a scenario for global warming into account, secondly measured weather data at the Fraunhofer ISE for the summer period 2003 are considered (denoted ISE2003). The German summer 2003 was characterized by persisting heat waves and high maximum temperature up to 38°C (Figure 5). During 42 nights the ambient air temperature did not fall below 18°C. The measured mean radiation in Freiburg 2003 amounts to 1261kWh/m², and is therewith significantly above the mean values of 1109 kWh/m² given in the former TRY weather database for the reference station Freiburg.

BUILDING MODEL: The investigated office is described as one thermal zone (floor area 20 m², room height of 3.10 m.) Counting the exterior envelope, floor, and ceiling surfaces, the building mass is approximately 652 kg/m² of floor area. The heavy weight of construction is due to layers of high-density concrete, 175 mm thick in the exterior walls and 290 mm thick in the floors. Two office workers occupy the room contributing together with the lighting and the office equipment 280 W of sensible and 60 W latent (approx. 40 g water per person) internal gain during workdays from 8 am to 6 pm. Ventilation of the required fresh air of 30 m³/(person*h) is applied during the occupancy. Infiltration of the office amounts to 0.2 ACH. The façade with a glass ratio of 62% has a true south-north alignment and a g-value of 58% and a U-value of 1.12. Solar internal Venetian blinds are lowered

completely (down=100%), if the irradiation on the outside vertical façade exceeds a threshold of $150W/m^2_{façade}$ resulting in a g-value of 42%. Adjacent rooms to the considered office are assumed to operate under similar operation and boundary conditions.

NIGHT VENTILATION: The air flow network consists of an air node for the thermal zone and the ambient environment, which are connected via modeled components including ventilation flaps from the ambient to the office, leakages of the building envelope, as well as an exhaust air fan. Mechanical nighttime ventilation with a varying ACH of 1, 2, 4, 6 and 8 precools the building structure outside the time of occupancy if (i) the operative room temperature exceed 22°C and (ii) if the ambient temperature is below the operative room temperature.

PLANT MODEL: The office is equipped with the particular energy delivery system (Table 1), as well as necessary piping and a circulation pump.

PCM: Commercially available micro-encapsulated paraffin (PCM) is integrated in the plaster of the ceiling as a latent heat storage, characterized by the following thermal and physical properties: Density 860 kg/m³, thermal conductivity 0.2 W/(mK), weight 2.6 kg/m², sensible specific heat capacity 1.0 kJ/(kgK), latent heat of 18 KJ/(kg), and melting range 19 to 22°C.

OPERATION MODES: Whereas the ground as heat sink is available over 24 hours, the operation of the cooling tower is mainly limited to the cooler nighttime hours. This results in the following operation modes: *Nighttime operation*: The plant system operates during 10 pm and 6 am maintaining a cooling setpoint of 20°C operative room temperature (heat sink is ground or ambient air). *Daytime operation*: The plant system operates during 7 am and 6 pm maintaining a cooling setpoint of 24°C operative room temperature (heat sink is ground). *Continuous operation*: The plant system operates during occupancy (8 am to 6 pm) maintaining a cooling setpoint or 24°C and during unoccupied times precooling to a setpoint of 20°C operative room temperature (heat sink is ground). Water supply temperature or flow control is not considered.

HEAT SINKS: Since again emphasize is not given to the modeling approach of the natural heat, water supply temperatures provided by the heat sink are calculated separately and read in the simulation as external input-file. This represents the source adequate enough; however, the cooling potential of the source is not described thoroughly, since in this case water supply temperatures are not a function of water return temperatures. The plant system is operated in direct cooling, i.e., water supply temperatures from the source are given directly to the plant without using an additional heat exchanger.

Due to the evaporative heat rejection, wet cooling towers provide significantly lower water temperatures than achievable with "air cooled" heat rejection devices, since the cooling performance is related to ambient wet bulb conditions. The monitored cooling tower at the building site has a cooling power of 3 kW and an efficiency of 35%.

As against, the ground changes its temperature much slowlier than the ambient air. The deeper in the ground, the more the ambient temperature is attenuated, and in a depth of about 50 to 100 m the ground remains at an almost steady temperature level which is around one Kelvin higher than the annual mean ambient air temperature. Figure 4 illustrates water supply and return temperatures of 40 (Energon Ulm) and 5 (SIC Freiburg) bore-hole heat exchangers (BHEX), respectively, which serve low-energy office buildings. Though different for each building site, operation mode and ground conditions, measured water supply temperatues in summer range usually between 11 and 21 °C, can fluctuate within a day around 2 Kelvin, and, obviously, increase over the course of the cooling period. For simulation purpose, water supply temperatures are simplified as sinus curve with an amplitude of two Kelvin within a 24 hour cycle period; starting at 16°C and gradually increasing over the three summer month of operation to 19°C. Considering daytime operation mode, supply temperatures culminate around 6 pm (end of occupancy) and in nighttime operation mode around 6 am. Applying the continuous operation mode, water supply temperatures are described as a linear function increasing over the cooling period.

A global warming scenario not just accounts for higher ambient air temperatures and an increased amount of solar radiation, but will effect the ground temperatures in a long term perspective, too. For the given research purpose, water supply temperatures are increased by two Kelvin compared to the TRY12 conditions, since the difference of the annual mean ambient temperature between TRY12 and ISE2003 amount to 2.0 K (Table 3).

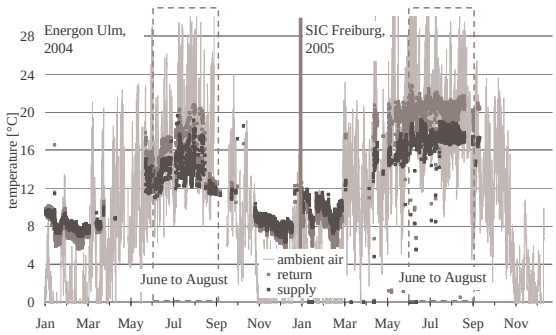

Figure 4 Measured supply and return water temperature of BHEX which serve two low-energy office buildings with different energy concepts and operation of the BHEX. Emphasized is the main cooling period, June – August.

Table 2 Weather data: Monthly mean, monthly mean minimum and maximum temperatures; TRY12, ISE2003.

	June		July		August	
AT [°C]	TRY 12	ISE 2003	TRY 12	ISE 2003	TRY 12	ISE 2003
monthly av	16.7	23.9	18.8	22.2	19.6	25.0
monthly av min	11.9	17.9	13.2	16.8	13.6	18.3
monthly av max	21.3	30.4	24.0	27.5	25.5	31.7
annual mean	TRY12: 10.4 / ISE 2003: 12.3					

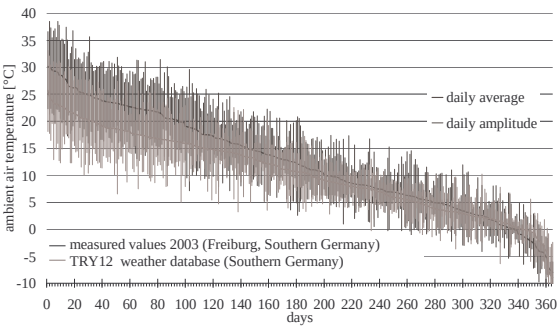

Figure 5 Distribution frequencies of daily mean ambient air temperature with associated day-night amplitude; TRY12, ISE2003.

Table 3 Comparison of ambient air temperature and water supply temperatures from BHE). Considered are values for Freiburg 2005 and Ulm 2004 (Figure 4) as well as chosen values for the TRY12 weather data base and for the global warming scenario (ISE2003 weather).

temperature [°C]	ISE 2005	Ulm 2004	TRY 12	ISE 2003
annual mean ambient air	11.4	7.6	10.4	12.3
mean ambient air (June - Aug)	19.8	16.3	18.4	23.7
mean water supply from BHEX	17.1	14.5	17.0	19.0
min. water supply from BHEX	14.0	11.0	15.0	17.0
Max. water supply from BHEX	19.0	18.0	19.0	21.0
mean daily amplitude for water supply from BHEX [K]	2	2	2	2

ANALYSIS OF RESULTS

THERMAL COMFORT ANALYSIS

The thermal interior comfort of the office room during the summer period June to August is evaluated concerning the operative room temperatures and afore introduced comfort means, taken only the hours of occupancy into account; that is workdays from 8 am to 6 pm. As an example, time series of operative room temperatures are given for the concrete core conditioning system in nighttime operation mode and nighttime ventilation in, demonstrating their dependency on the ambient conditions. The frequency distribution in Figure 6 illustrates the characteristic of the operative room temperature for all examined concepts over the course of occupancy for the examined period. Exemplarily for concrete core and grid conditioning under TRY12 weather, values are smoothly distributed without outliers over 650 hours of occupancy which allows for drawing on monthly averaged operative room temperatures as well as frequencies of exceeding a threshold of 24.5°C (ISO 7730) (Figure 7) for an overall evaluation of thermal comfort.

RESULTS:

- Considering night ventilation concepts, applied air change rates should not be less than 4 ACH to effectively discharge the heat loads and to cool the building structure. However, persistent heat waves and higher nighttime ambient air temperatures deplete the cooling potential of the ventilation concept resulting in unsuitable room conditions. Though hourly air change rates higher than 8 can result in a thermal room performance equivalent to grid conditioning or radiant cooling panels (operated with low flow rates in nighttime operation mode), they are technically and economical hardly acceptable.
- The water supply temperature, the flow rate, as well as the operation mode of the plant are crucial factors for the thermal room performance taking hydronic radiant cooling systems into account. Reducing the water supply temperature has indeed a more considerable effect on the operative room temperature. Nevertheless, minimum supply temperatures are restricted due to the problem of water condensation on the surface of the activated building component which is discussed later on. Increasing water flow rates has a minor impact on the reduction of operative room temperatures, e.g., increasing the flow rate by 4 l/(m²h) reduces the average room temperature by around 0.5 K. This issues still requires validation by means of measurements.
- Results show that during moderate summer conditions, the cooling performance of a wet cooling tower is apparently similar to bore-hole heat exchangers, yet, the performance of the cooling tower is stronger connected to the ambient air conditions. Besides, large-scale towers are difficult to integrate at the building site. As for a global warming scenario, the cooling power of both heat sinks is diminished. However, temperature developments in the ground have to be considered over a long-term period, whereas the cooling performance of a wet cooling tower decreases immediately with rising ambient wet bulb temperatures.
- Is a nighttime operation mode required for the plant, than the application of a concrete core conditioning system activate the concrete slab of the ceiling most effective resulting in a significantly improved thermal comfort performance compared to the other systems.
- If the plant is operated during the hours of occupancy, grid conditioning system results is the least amount of hours exceeding 24.5°C due to the quicker response time as against concrete core conditioning system.

- As expected, a continuous operation of the plant system achieves the best thermal comfort performance, although it is not really beneficial for the radiant cooling ceiling and the grid conditioning system, since the thermal performance is here marginally improved compared to the daytime operation.
- As portrayed in Figure 8, for the nighttime operation mode operative room temperatures violate the upper comfort thresholds for 65% occupant satisfaction and stay just in the given comfort range for the nighttime and continuous mode, respectively. Consequently, the application of TABS requires notably reduced internal loads, in the given example asking for a better solar shading system with a total g-value around 20 to 30%.
- Although the grid conditioning system with PCM does not differ much in the average operative room temperature from the system without PCM, its operation results in decreased daily average maximum temperatures (up to 0.5 K) and up to 24% less working hours exceeding 24.5°C. The improvement of the thermal comfort due to PCM is most prominent for the nighttime operation because of its heat storage effect.

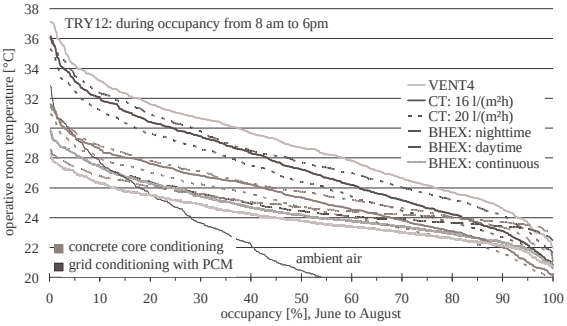

Figure 6 Frequency distribution of operative room temperatures for the time of occupancy considering concrete core and grid conditioning with PCM, TRY12.

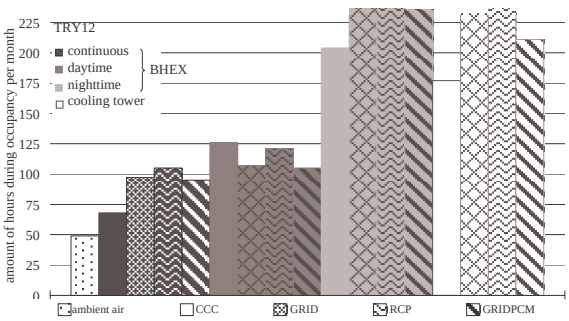

Figure 7 Frequency of working hours in July where the operative room temperature exceeds a comfort threshold of 24.5°C according to ISO 7730.

ENERGY CONSUMPTION

The analysis of the energy consumption takes both end and primary energy into account, as well as the coefficient of performance (COP) for evaluating the primary energy consumption in $kWh_{therm}/kWh_{primary_energy}$ (Figure 9).

Table 4 Monthly mean operative room temperatures.

			TRY 12 weather			ISE2003 weather		
	temperature °C		Jun	Jul	Aug	Jun	Jul	Aug
	ambient		19.2	20.8	23.0	27.3	24.2	28.7
ventil -ation	ACH	4	26.5	29.0	30.8	34.3	33.6	38.1
		6	26.2	28.0	29.8	33.2	32.1	36.4
		8	25.6	27.7	29.3	32.5	31.4	35.5
heat sink: cooling tower	16 l/(m²h)	CCC	23.5	25.6	26.7	29.4	28.0	30.9
		GRID	26.1	28.3	29.8	32.7	31.0	34.6
		RCP	26.0	28.5	29.9	32.6	31.3	34.7
		PCM	25.1	27.8	29.3	32.5	30.9	34.6
	20 l/(m²h)	CCC	23.1	25.2	26.0	28.8	27.4	30.1
		GRID	25.6	27.8	29.1	32.1	30.5	33.9
		RCP	25.7	28.1	29.4	32.3	30.9	34.2
		PCM	24.8	27.0	28.4	31.9	30.0	33.8
heat sink: bore-hole heat exchanger	nighttime	CCC	24.5	25.9	27.4	29.4	28.0	30.8
		GRID	26.8	28.4	30.3	32.7	31.0	34.6
		RCP	26.9	29.7	30.6	32.6	31.3	34.7
		PCM	25.8	28.0	30.2	32.6	30.9	34.6
	daytime	CCC	24.6	24.8	25.6	29.4	29.1	32.8
		GRID	24.5	24.8	25.9	32.6	32.0	35.4
		RCP	24.5	24.8	26.0	32.7	32.2	35.6
		PCM	24.5	24.7	25.8	32.6	32.0	35.4
	continuous	CCC	23.2	23.9	25.0	26.4	26.2	28.2
		GRID	23.9	24.5	25.7	27.4	27.0	29.3
		RCP	23.9	24.6	25.8	27.5	27.1	29.4
		PCM	23.7	24.4	25.6	27.3	27.0	29.3

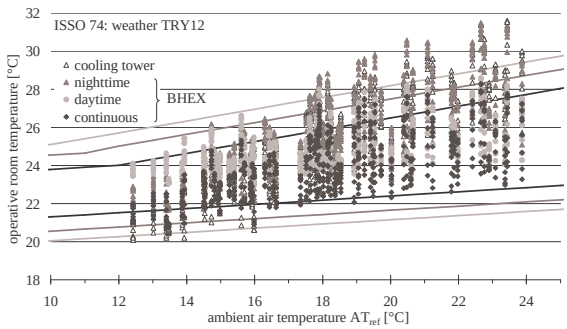

Figure 8 Thermal comfort: ISSO 74 charts show the temperature range for 90 (black line), 80 (dark grey line) and 65% (light grey line) users satisfied with the room temperature.

Long-term monitoring in buildings with night ventilation revealed that the electrical power consumption of an energy efficient fan and duct system amounts to approximately 0.25 W/(m³h) (Pfafferott 2003). The analysis of the hydronic systems bases on the assumption that the pressure drops over the energy delivery system are significant lower, than over the distribution system where given maximum pressure drops over one circuit amount to 30 kPa for concrete core conditioning, 20 kPa for the radiant cooling ceiling and around 10 kPa for the grid conditioning system (Glück 2003). Therefore, as given by the long-term monitoring analysis of low energy buildings equipped with TABS, the electrical power consumption of the circulation pump is defined as 0.036 Wh/l and 0.040 Wh/l for a flow rate of 16 l/(m²h) and 20 l/(m²h), respectively, for all

delivery systems. Further, the power of the wet cooling power (fan and pump for sprayed water) at the building site was measured to 225 W and the primary circulation pump was monitored to consume around 92 W for one bore-hole heat exchanger.

RESULTS: All systems work most efficient in the nighttime mode considering bore-hole heat exchangers with a monthly averaged COP of 3 to 5 related to the primary energy consumption. Of course, the COP decreases with longer operation hours due to the energy consumption, but with an associated improved thermal comfort. Operating the cooling tower results in COPs of 1 to 2 which can be improved using a cooling tower with a higher efficiency. These conclusions also hold for the global warming scenario.

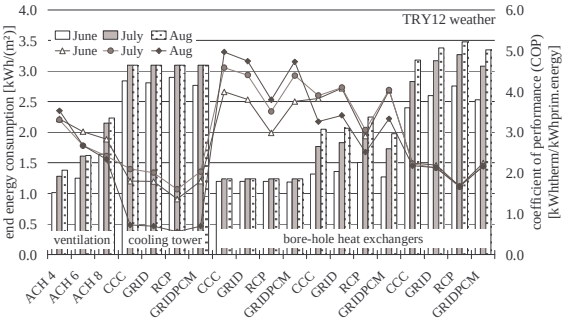

Figure 9 End energy consumption [kWh/m²] as well as COP [$kWh_{therm}/kWh_{prim_energy}$] for the evaluation of primary energy considering the cases in the following order: ventilation, cooling tower, BHEX (nighttime), BHEX (daytime) and BHEX (continuous), TRY12.

CONDENSATION

Reduced water supply temperatures improve both the thermal comfort performance and the energy efficiency due to reduced flow rates. Anyway, water supply temperatures for radiant cooling systems are limited due to condensation problems at the surface of the activated building component. Though not really critical for the operation of a concrete core conditioning system (Table 5), a supply temperature control for the grid conditioning system as well as for the radiant cooling ceiling might be necessary, in order to use the maximum cooling potential provided by the sink and to prevent condensation.

Table 5 Hours during the three month period, where dry bulb temperature falls 0.5 Kelvin below the dew point temperature for all water driven systems.

cooling tower				bore-hole heat exchanger											
16 l/(m²h)				nighttime				daytime				continuous			
CCC	GRID	RCP	PCM	CCC	GRID	RCP	PCM	CCC	GRID	RCP	PCM	CCC	GRID	RCP	PCM
TRY12 weather															
0	7	37	9	0	7	37	9	9	18	52	26	27	63	143	62
ISE2003															
0	0	0	0	0	0	1	0	0	2	7	1	0	5	33	5

SUMMARY

With reference to the hypothesis stated in the introduction, the following conclusions can be drawn from this study:

(1) Thermal comfort is significantly improved by hydronic radiant cooling systems, especially during persisting heat waves.

(2) If a nighttime operation mode is required for the plant, the concrete slab of the ceiling is activated most effective by concrete core conditioning. Then, the thermal comfort performance is significantly improved compared to the other systems.

(3) If the plant is operated during the hours of occupancy, grid conditioning system results is the least amount of hours exceeding 24.5°C due to the quicker response time as against concrete core conditioning system.

(4) Although the grid conditioning system with PCM does not differ much in the mean operative room temperature from the system without PCM, its operation results in decreased daily mean maximum temperatures (up to 0.5 K) and up to 24% less working hours exceeding 24.5°C.

REFERENCES

Boersta, A.C., Hulsman, L.P. and van Weele, A.M. 2005. ISSO 74 Kleintje Binnenklimaat. Stichting ISSO, Rotterdam. (In Dutch)

CEN/BT WG 173 EPBD. 2006. Explanation of the general relationship between various CEN standards and the Energy Performance of Buildings Directive (EPBD).

Clarke, J.A.. 2001. Energy Simulation in Building Design. 2nd edition, Butterworth-Heinemann.

Glück, B. 2003. Umweltschonende Raumheizung und –kühlung mit Kunststoff-Kapillarrohrmatten. FIA-Projekt, Final Report, 032 7241 B. (in German)

Heim, D. and Clarke, J.A. 2004. Numerical modeling and thermal simulation of PCM-gypsum composites with ESP-r. Energy and Buildings 36(8): 795-805.

Kalz, D., Pfafferott, J., Schossig, P. and Herkel, S. 2007. Thermoaktive Bauteilsysteme mit integrierten Phasenwechselmaterialine – eine Simulationsstudie. Bauphysik, 29(1):27-32. (in German)

Laouadi, A. 2004. Development of a radiant heating and cooling model for building energy simulation software. Building and Environment, 39(4): 421-431.

Schossig, P., Henning, H.-M., Gschwander, S. and Haussmann, T. 2005. Microencapsulated Phase Change Materials integrated into Construction Materials. Solar Energy Materials and Solar Cells 89(2/3): 297-306.

Schossig, P., Henning, H.-M., Haussmann, T. and Raicu, R. 2003. Phase change materials in constructions. Phase Change Material Slurry Scientific Conference and Business Forum, Yverdon-les-bains Switzerland, Proceeding, p. 33-43.

Pfafferott, J. and Kalz. D. 2007. Thermoaktive Bauteilsysteme. FIZ Karlsruhe GmbH Bonn. ISSN 1610 – 8302. (German)

Pfafferott, J., Schiel, S. and Herkel, S. 2005. Bauteilkühlung – Messungen und modellbasierte Auswertung. Proceeding, 15th Symposium Thermische Solarenergie Bad Staffelstein OTTI, p. 422-427. (German)

Pafferott, J. 2003. Passive Kühlung mit Nachtlüftung. FIZ Karlsruhe GMbH Bonn. ISSn 1610 – 8302. (German)