OPERATION AND CONTROL OF ACTIVATED SLAB HEATING AND COOLING SYSTEMS

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ABSTRACT

Heating and cooling of buildings may be done by water based radiant systems, where pipes are embedded in the concrete slabs between each storey. Activating the building mass will reduce the peak load and transfer some of load to out side the period of occupancy. Because these systems operate at water temperature close to room the potential for use of renewable energy sources are increased

Due to the high energy consumption and first costs several European countries debate if air conditioning of buildings is to be recommended or prohibited by law. Air-conditioning will give better control of the indoor temperature and improve comfort and productivity. However, many examples of discomfort in air-conditioned buildings due to draught, noise and sick building syndrome, exist.

Because these types of systems are using building mass for heating and cooling it is often questioned how they must be designed, kind of control concept should be used and what are the performance. The present paper presents a parametric study of design issues and different control concepts, based on dynamic computer simulations.

To use these type of systems the building must be well designed. A combination of time control and water temperature control according to outside temperature conditions will provide acceptable indoor conditions and low energy consumption. Several examples of buildings with these type of systems is presented together with measured performance.

Key words: computer simulation, radiant heating, radiant cooling, comfort, control.

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1 INTRODUCTION

A new trend that started in the early nineties in Switzerland (Meierhans 1993, 1996) is to use the thermal storage capacity of the concrete slabs between each storey in multi-storey buildings to heat or cool buildings. Pipes carrying water for heating and cooling are embedded in the centre of the concrete slab.

By activating the building mass there will not only be a direct heating-cooling effect, but due to the thermal mass, the peak load will also be reduced and it will be possible to transfer some of the load outside the period of occupancy. Because these systems for cooling operate at water temperatures close to room temperature, they increase the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources.

Relatively small temperature differences between the heated or cooled surface and the space are typical for surface heating and cooling systems. This results in a significant degree of self control, because a small change in the temperature difference will influence significantly the heat transfer between the cooled or heated surface and the space.

In an earlier study, Olesen et.al. (2000) studied different control parameters for the summer season (time of system operation, intermittent operation of circulation pump and supply water temperature control) by dynamic computer simulation. It was found that operation of the system during the night was sufficient, intermittent operation of the pump was possible, and that the water temperature should be controlled over the season based on the outdoor temperature.

The present paper presents the results of additional dynamic computer simulations of such a system. In the present study two different climatic zones (Würzburg, Germany and Venice, Italy) are studied for both the summer and winter season. Further algorithms for water temperature control and the effect of a room temperature dead-band are investigated.

2 METHOD

The study was performed with the aid of the dynamic simulation program (TRNSYS 1998). The multidimensional heat transfer processes in the slab were modelled via a special module developed by Fort (1996). The following describes the test space and other boundary conditions, which were very similar to the conditions reported by Olesen et. al. (2000) and Hauser et. al. (2000).

2.1 Description of system and test space

The system considered is shown in Figures 1 and 2. The ceiling/floor consists of an 18 cm thick concrete slab with 20 mm plastic pipes embedded in the middle with 150 mm spacing. The slab is finished with 20 mm of acoustical insulation and 45 mm screed. Heat is supplied or removed by the heated or cooled water flowing in the embedded pipes. The mass flow rate of the system is constant at 350 kg/h.

The effect of heating and cooling the ceiling is described using a central room module in an office building with offices on either side (west and east) of the corridor. All neighbour rooms are assumed to have the same internal temperatures as the test space. This characterizes the thermal behaviour of all rooms that are at least two rooms away from the roof, corner and ground floor rooms. The geometrical dimensions of the room module are shown in *Figure 1*. Details of envelope are listed in Table 1.

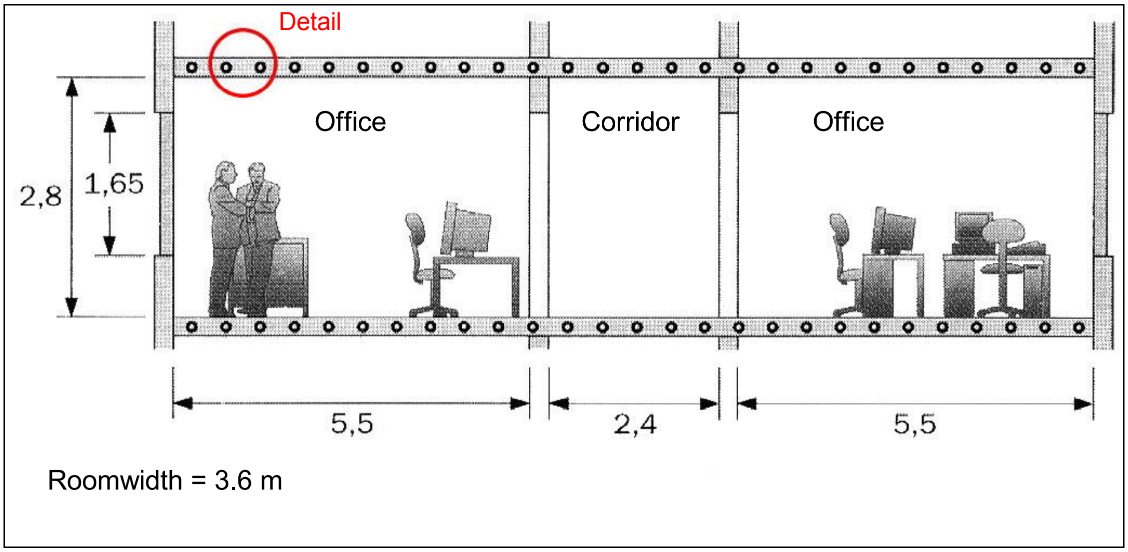


Figure 1. Central room module used for the computer simulation of a building with concrete slab cooling. All dimensions are in meters.

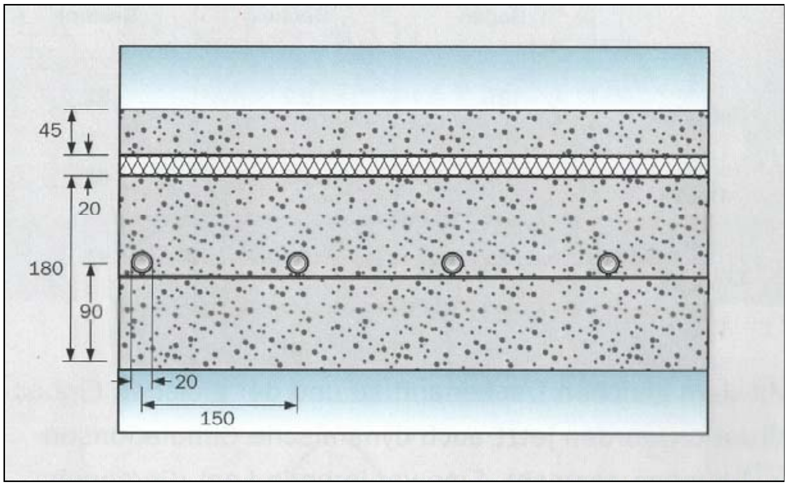


Figure 2. Position of the plastic pipes in the concrete slab between two stories.

The floor *(Figure 2)* consists of 45 mm screed (λ = 1.4 W/m²K, c = 1 kJ/kgK, ρ = 2000 kg/m³), 20 mm insulation (λ = 0.04 W/m²K, c = 1.5 kJ/kgK, ρ = 50 kg/m³) and 180 mm concrete

(λ = 2.1 W/m²K, c = 1 kJ/kgK, ρ = 2400 kg/m³). The outside pipe diameter is 20 mm and the spacing is 150 mm. The window covers 60 % of the outside wall..
The room volume is 55.44 m³ with a thermal capacity of 700 kJ/K.

Table 1: Thermal characteristics of the building components

		[mm]	*Density [kg/m³]*	*Conducting [W(mK)]*	*Capacity [Wh(kgK(]*	*Emission*
Floor ceiling	Screed Acoustical insulation Concrete	45 20 180	2000 50 2400	1,4 0,04 2,1	0,28 0,42 0,28	0,94
Outside wall, light U = 0,37	Aluminium Insulation Aluminum	2 100 2	2600 30 2600	200 0,04 200	0,28 0,28 0,28	0,30
Outside wall, heavy U = 0,37	Plaster Insulation Sand lime brick Plaster	8 80 240 15	1000 40 1200 1200	0,7 0,04 0,56 0,35	0,28 0,42 0,28 0,28	0,82
Internal wall, light	Plasterboard Insulation Plasterboard	25 60 25	900 20 900	0.21 0,04 0,21	0,28 0,28 0,28	0,82
Internal wall, heavy	Plaster Sand lime brick	15 115	1200 1800	0,35 0,99	0,28 0,28	0,82 0,93
Window	Wooden frame, 30 % Glass	U_{frame} 2,1 W/(m²K) U_{glass} 1,1 W/(m²K) U_{window} 1,4 W/(m²K) g 0,58				

Table 2: Design day ***outdoor*** *temperatures for Würzburg, Germany and Venice, Italy.*

City	Lat. [°]	Long. [°]	Elev. [m]	Heating Dry Bulb [°C]		Cooling Dry Bulb [°C]	
				99,6%	99%	0,4%	2%
Venice	45.30 N	12.20 E	6	-4,9	-3,1	30,8	28,2
Würzburg-Frankfurt	50.05 N	8.60 E	113	-11	-8,2	30,3	26,7

2.2 Boundary conditions

The meteorological ambient boundary conditions correspond to those of Würzburg/Germany and Venice/Italy. The external temperature data for winter and summer design days are shown in *Table 2*. Summer was the period from 1 May to 30 September, and winter was the period from 1 October to 30 April.
The time of occupancy was Monday to Friday from 8.00 to 17.00, with a lunch break from 12.00 to 13.00.
The system was in operation only outside the period of occupancy, from 18:00 to 06:00.

Internal Heat Sources: During occupied periods 550 W corresponding to 27.8 W/m$^{2.}$

	This corresponds to two occupants, two computers, a printer and light. During the lunch break 350 W corresponding to 17.7 W/m^2, 50% convective, 50% radiant.
Moisture Production:	During occupation, 100 g/h.
Ventilation (ach):	Outside time of occupation 0.3 h^{-1} (infiltration). During occupation 1.5 h^{-1} (~ 11 l/s per person).
Sun Protection:	During occupation by direct exposure of sunlight and operative temperature above 23°C, reduction factor z = 0.5.

2.3 Control parameters studied

Two control parameters were studied:

Control of water temperature
Dead-band for room temperature

2.3.1 Control of water temperature

The goal for the system used in the present study is to operate water temperatures as close to the room temperature as possible. If very high or very low water temperatures are introduced into the system it may result in over-heating or under-cooling.

In the present study, the supply water temperature was controlled so that it was not lower than the dew point in the space. For this purpose a humidity balance (latent loads from people, outside humidity gain from ventilation) was also included in the simulation. It was then possible to calculate the dew point in the room for each time step in the simulation.

Instead of controlling the supply water temperature it may be better to control the average water temperature. The return water temperatures are influenced by the room conditions. By maintaining a constant supply water temperature, an increase in internal loads from sun or internal heat sources will increase the return temperature. The average water temperature will then increase and the cooling potential will decrease. If instead the average water temperature (½(t_{return} – t_{supply})) is controlled, an increase in return temperature will automatically be compensated for by a decrease in supply water temperature.

In well designed buildings with low heating and cooling loads it may be possible to operate the system at a constant water temperature. The following concepts for water temperature control were studied:

Supply water temperature is a function of outside temperature according to the equation:

$$t_{supply} = 0{,}52 * \left(20 - t_{external}\right) + 20 - 1{,}6 * (t_o - 22) \quad \text{°C} \quad \text{(case 801)}$$

Average water temperature is a function of outside temperature according to:

$$t_{average} = 0{,}52 * \left(20 - t_{external}\right) + 20 - 1{,}6 * (t_o - 22) \quad \text{°C} \quad \text{(case 901)}$$

where

t_o = Operative Temperature

Average water temperature is constant and equal to: 22°C in summer and 25°C in winter. (case 1201)

Supply water temperature is a function of outside temperature according to the equation:

$$t_{supply} = 0{,}35 * \left(18 - t_{external}\right) + 18 \quad \text{°C} \quad \text{summer} \quad \text{(case 1401)}$$

$$t_{supply} = 0{,}45 * \left(18 - t_{external}\right) + 18 \quad \text{°C} \quad \text{winter} \quad \text{(case 1401)}$$

2.3.2 Dead-band of room temperature

To avoid a too frequent change between cooling and heating, it is recommended that the circulation pump be stopped during a certain room temperature range, i.e., dead-band. In the study by Olesen et. al. (2000) a dead-band of 22°C to 23°C was used. This means that when the room operative temperature increases above 23°C, the system will start in the cooling mode. If the room operative temperature is less than 22°C, the system will start in the heating mode. In between the circulation pump is stopped.

In the present study the following dead-bands were tested:

22 – 23°C (case 0901-1)
21 – 23°C (case 0901-8)
21 – 24°C (case 0901-9)

2.3.3 Use of weather forecast

As the reaction time of building and the activated slab is very long, it may be an advantage to control the water temperature according to the weather forecast of external temperature. By using a test reference year (Würzburg or Venice) the forecast can be made 100% correctly. **Table 3** shows the cases tested. The supply water temperature (t_{sup}) was controlled according to the outside temperature following the same algorithm, but a different time average of external temperature (t_{ex}) was used as input. The dead-band was the same for all cases. The simulation was made for the whole year.

Table 3 - Boundary conditions

case	Water temperature	External temperature	dead band
18	T_{sup} = 0.5*(18-t_{ex})+18	mean value next 24 hours	21.5-23.5
19	T_{sup} = 0.5*(18-t_{ex})+18	mean value next 72 hours	21.5-23.5
20	T_{sup} = 0.5*(18-t_{ex})+18	mean value 12 hours around actual time	21.5-23.5
21	T_{sup} = 0.5*(18-t_{ex})+18	mean value 24 hours around actual time	21.5-23.5
24	T_{sup} = 0.5*(18-t_{ex})+18	instant value	21.5-23.5

3 RESULTS AND DISCUSSION

The simulations were made for both an east- and a west-facing room. Only results for a west-facing room are presented in this paper. In a pre-test it was found that the highest exposures occurred in the room facing west.

Results from the summer period 1 May to 30 September and the winter period 1 October to 30 April are presented.

The total number of hours in each period is ~3690, number of working days ~109 and number of working hours ~981. The results will be evaluated based on comfort (operative temperature ranges, daily operative temperature drift during occupancy) and energy (running hours for circulation pump, energy removed or supplied by the circulated water).

The calculated operative temperatures may be compared to the comfort range 23 to 26°C recommended for summer (cooling period) and 20 to 24°C recommended for winter (heating period) (ASHRAE 1992; CEN 1998; ENISO 1993). This is based on a fixed level of clothing insulation for summer (0.5 clo) and winter (1.0 clo), which may not be relevant for the whole period.

3.1 Study of water temperature control

The results of the simulation are shown in *Table 4* for summer conditions and in *Table 5* for winter conditions. Figure 3 is showing trends of external temperature, calculated operative temperature, calculated water supply temperature based on case 0901, actual supply water temperature and return water temperature for a summer week in Venice. The supply water temperature was controlled as a function of the external temperature and the internal temperature according to eq. 0901. But most of the time the supply water temperature was limited by the dew-point, so even if the calculated supply water temperature was as low as 5 °C it never went below 17 °C, because of the high dew-point in Venice in September. The shaded area is showing the time of occupancy. The room temperature drift everyday between 24,5 and 27,5 °C.

The operative temperature of the cases *0801*, *0901* and *1401 (Table 4)* is for most of the time (>85%) in a comfort range (22-26°C). In Würzburg 27°C is never exceeded and 26°C is exceeded less than 5% of the time. In Venice only 5% of the temperatures are above 27°C. The difference between controlling the supply water temperature (case 0801) or the average water temperature (case 0901) is very small. In the case 1401 the control does not take into account the internal operative temperature, but the results are almost identical to cases 0801 and 0901. With a constant average water temperature (22°C) the cooling effect is too low and the operative temperature is often too high (60% of the time above 27°C in Venice and 27% in Würzburg).

The energy use is the same for the cases *0801*, *0901* and *1401* in Venice. For Würzburg, case 1401 is the energy use, but it is about 10% lower than case 801 and 901. Energy use in case 1201 with a constant water temperature is relatively high.

The pump running time for case 1401 is equal to or lower than the other cases.

In the summer, case *1401* is overall better than the others. Due to the warmer climate in Venice *(Table 2)* the room temperatures are higher, and energy use and pump running time are also higher compared to Würzburg.

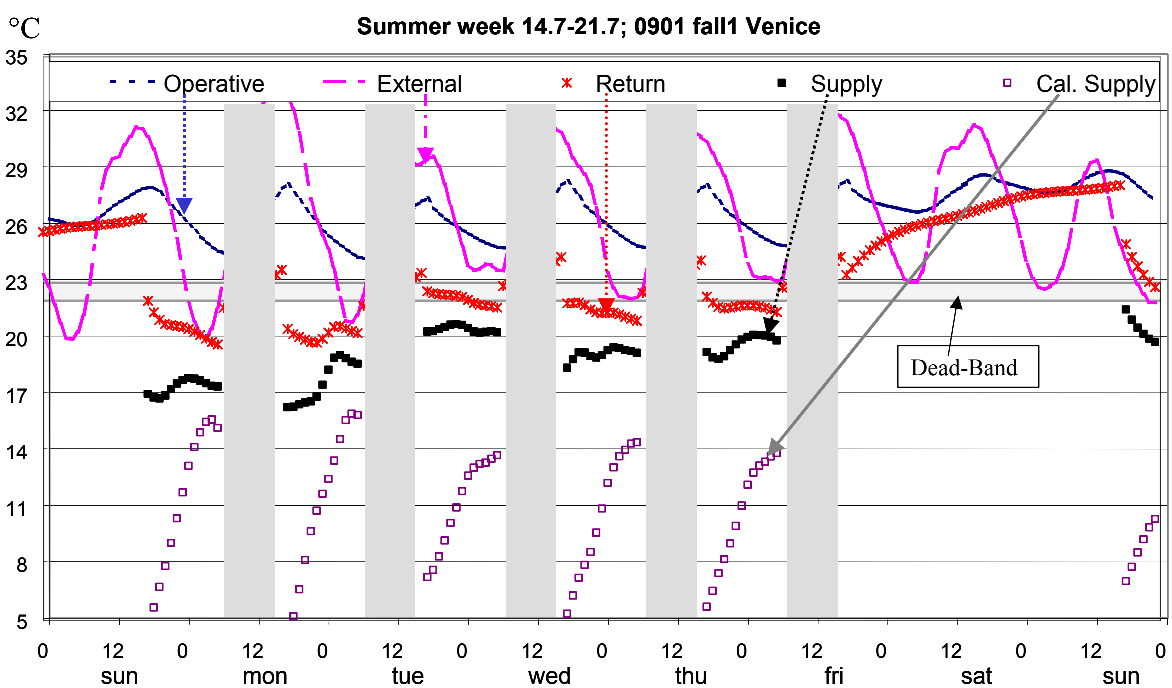


Figure 3. Trend curves for external temperature, operative temperature, calculated water supply temperature according to equation 0901, water supply temperature (limited by dew-point) and return water temperature. September week in Venice. The shaded area is the time of occupancy.

Table 4: Operative temperatures, temperature drift, pump running time and energy transfer for different water temperature control strategies. Summer conditions. Dead-band 22 – 23°C. Ventilation rate: 0.3 ach from17:00 to 8:00, 1.5 ach from 8:00 to 17:00.

		May to September Time of operation 18:00-06:00							
		Venice				Würzburg			
Water temperature control		Supply = F (outside) 0801	Average = F (outside) 0901	Average = 22°C 1201	Average= F (outside) 1401	Supply=F (outside) 0801	Average= F (outside) 0901	Average= 22°C 1201	Average= F (outside) 1401
Operative temperature interval	°C	%	%	%	%	%	%	%	%
	<20	0	0	0	0	0	0	0	0
	20-22	0	0	0	0	3	3	1	5
	22-25	56	58	8	56	75	78	30	77
	25-26	26	25	13	25	18	16	21	14
	26-27	13	12	19	14	5	4	22	4
	>27	5	5	60	5	0	0	27	0
Temperature drift [days]	<1	0	0	0	0	3	2	6	4
	1-2	9	9	14	10	26	27	26	24
	2-3	56	54	65	49	33	33	46	35
	3-4	35	37	21	41	38	38	22	37
	4-5	0	0	0	0	1	1	0	1
	5-6	0	0	0	0	0	0	0	0
	>6	0	0	0	0	0	0	0	0
Pump running	hours	1254	1190	1417	1214	1091	971	1327	953
	% of time	34	32	39	33	30	26	36	26
Energy kWh	Cooling	1104	1109	1297	1106	763	785	978	749
	Heating	1	2	0	0	29	41	2	2

Table 5: Operative temperatures, temperature drift, pump running time and energy transfer for different water temperature control strategies. Winter conditions. Dead-band 22 – 23°C. Ventilation rate: 0.3 ach from17:00 to 8:00, 1.5 ach from 8:00 to 17:00.

		October to April Time of operation 18:00-06:00							
		Venice				Würzburg			
Water temperature control		Supply=F (outside) 0801	Average= F (outside) 0901	Average= 25°C 1201	Average= (outside) 1401	Supply= F (outside) 0801	Average= F (outside) 0901	Average= 25°C 1201	Average= F (outside) 1401
Operative temperature interval	°C	%	%	%	%	%	%	%	%
	<20	0	0	0	1	0	0	4	4
	20-21	1	1	6	14	9	7	19	24
	21-23	72	75	50	63	77	80	50	63
	23-24	14	15	5	14	8	7	7	7
	24-26	12	10	23	8	6	5	15	2
	>26	0	0	16	0	0	0	5	0
Temperature drift [days]	<1	33	34	30	32	57	57	58	57
	1-2	44	43	49	41	29	29	28	29
	2-3	21	21	20	23	12	12	13	13
	3-4	2	2	0	4	2	2	1	2
	4-5	0	0	0	0	0	0	0	0
	5-6	0	0	0	0	0	0	0	0
	>6	0	0	0	0	0	0	0	0
Pump running	hours	837	642	1487	1166	813	664	1533	1322
	% of time	16	13	29	23	16	13	30	26
Energy kWh	Cooling	144	144	143	143	57	64	63	45
	Heating	551	554	407	421	816	834	684	717

Also for the winter period *(Table 5)* the cases 801, 901 and 1401 result in the most comfortable conditions. In Venice the room temperatures exceed the interval 20-24°C less than 12% of the time. In case 1401 the room temperature is, however, below 20°C for 4% of the time.

On the energy side, case 1401 is again about 10% better than cases 801 and 901, but the pump running time is significantly higher.

In winter the energy use in Würzburg is as expected higher than in Venice.

It is clear that with proper control the activated slab system is not only capable of reducing the indoor temperatures to a comfortable range, but also, as the only heating system, of heating up the space to the comfort range.

Table 6: Operative temperatures, temperature drift, pump running time and energy transfer by different room temperature dead-bands. Control of water supply temperature according to outside and internal temperature (case 0901). Summer conditions. Ventilation rate 0.8 ach

	May to September Time of operation 18:00-06:00						
		Venice			Würzburg		
Room temperature dead-band		22-23 °C 0901-1	21-23 °C 0901-8	21-24 °C 0901-9	22-23 °C 0901-1	21-23 °C 0901-8	21-24 °C 0901-9
Operative Temperature interval	°C	%	%	%	%	%	%
	<20	0	0	0	0	0	0
	20-22	0	0	0	2	6	5
	22-25	58	58	38	81	78	69
	25-26	25	25	33	14	14	20
	26-27	12	12	22	2	2	6
	>27	5	5	7	0	0	0
Temperature drift [days]	<1	0	0	0	0	0	0
	1-2	5	5	5	19	19	19
	2-3	44	44	44	31	31	32
	3-4	51	51	51	49	49	48
	4-5	0	0	0	1	1	1
	5-6	0	0	0	0	0	0
	>6	0	0	0	0	0	0
Pump running	hours	1094	1094	878	709	657	378
	% of time	30	30	24	19	18	10
Energy kWh	Cooling	1035	1035	983	669	657	606
	Heating	0	0	0	50	25	15

3.2 *Study on room temperature dead-band*

To minimize the risk for both heating and cooling within the same day and also to decrease pump running time, it is recommended to let the building float within a certain room temperature interval, i.e. dead-band. In the study by Olesen et. al. (2000) it was always 22-23°C. In the present study, two additional dead-bands, 21-23°C and 21-24°C were tested. The results for the summer period are shown in *Table 6* and for the winter period in *Table 7*. In all cases the supply water temperature was controlled according to case 901, with a constant ventilation rate of 0.8 ach for the whole day.

For the summer period, dead-bands of 22-23°C and 21-23°C gave the same results as regards operative temperature distribution, energy use and pump running time. The dead-band 21-24°C resulted in a somewhat higher room temperature, especially in Venice. The pump running time decreased significantly, but the energy use was about the same as for the two other dead-bands.

In winter, the greatest effect is achieved by lowering the dead-band from 22 to 21°C. This reduces the energy for heating by 20% and extends the time in which the operative temperatures are within the range 20-21°C, although always higher than 20°C.

Conclusions of the dead-band analysis. By optimising the dead-band, the energy use for heating-cooling and running the pump can be reduced without sacrificing comfort. The dead-band should not be larger than 2 K.

Table 7: Operative temperatures, temperature drift, pump running time and energy transfer by different room temperature dead-bands. Control of water supply temperature according to outside and internal temperature (case 0901). Winter conditions. Ventilation rate 0.8 ach.

		October to April Time of operation 18:00-06:00					
		Venice			Würzburg		
Room Temperature dead-band		22-23 °C 0901-1	21-23 °C 0901-8	21-24 °C 0901-9	22-23 °C 0901-1	21-23 °C 0901-8	21-24 °C 0901-9
Operative temperature interval	°C	%	%	%	%	%	%
	<20	0	0	0	0	0	0
	20-21	1	8	8	2	13	13
	21-23	62	71	68	78	77	77
	23-24	27	13	12	16	7	7
	24-26	10	7	11	4	2	2
	>26	0	0	0	0	0	0
Temperature drift [days]	<1	0	0	0	5	1	1
	1-2	49	47	47	64	69	69
	2-3	43	44	44	22	22	22
	3-4	8	9	9	9	9	9
	4-5	0	0	0	0	0	0
	5-6	0	0	0	0	0	0
	>6	0	0	0	0	0	0
Pump running	hours	761	526	443	841	634	594
	% of time	15	10	9	17	12	12
Energy kWh	Cooling	101	83	61	35	19	11
	Heating	842	713	695	1194	1138	1113

3.3 *Study on using weather forecast*

The results in *Figure 4* show the distribution of operative temperature during working time. There is no significant difference between the cases. So no benefits are obtained by trying to use a predicted future temperature. In real life, an additional factor will be how to correct the weather prediction. So it may even be worse to use the predicted weather data as input for the control. It should be mentioned that for the 24- or 72-hour average of the future outdoor temperature, the water supply temperature is constant during the time of operation 18:00 to 06:00.

Also when looking in detail at one week (*Figure 5*) the same results are obtained independent of the way in which the outdoor temperature is used.

Figure 4. Distribution of operative temperature during working time. Y-axis is the number of hours in the given temperature range (X-axis). Total number of working hours are ~3690 hours.

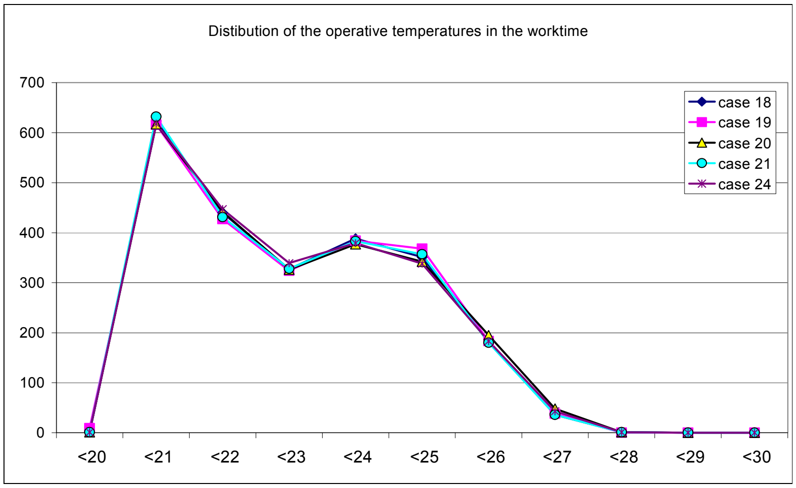
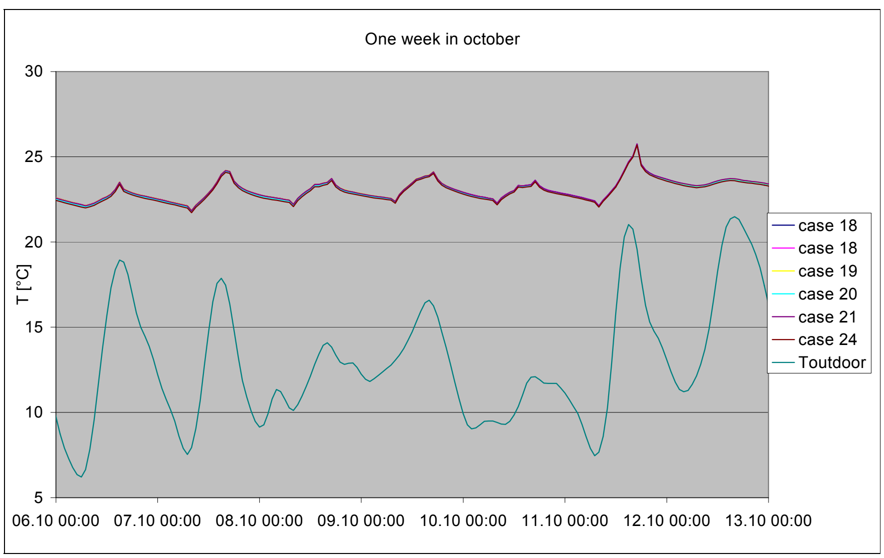


Figure 5. Operative temperature during a week in October.



4 CONCLUSION

The results of a dynamic computer simulation of different control concepts for a water-based radiant cooling and heating system with pipes embedded in the concrete slabs have been presented. The system was studied for both the summer period May to September and the winter period October to April in two geographical locations, Venice, Italy and Würzburg, Germany.

The best performance regarding comfort and energy is obtained by controlling the water temperature (supply or average) as a function of outdoor temperature. There is no need to take into account the room temperature.

The actual outside temperature can be used as input to the control. No benefits are obtained by using an average outdoor temperature or a future predicted outdoor temperature based on the weather forecast.
The energy performance (energy use for heating and cooling, pump running time) can be reduced further by introducing a 2 K room temperature interval (dead-band), where the circulation pump is stopped.
The system was able to keep the room temperatures within a comfortable range, in both summer (cooling) and winter (heating), and in both climatic zones.

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