

Radiant heating and cooling by embedded water-based systems

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ABSTRACT

Because of high initial costs, high energy consumption and often unacceptable indoor climate (SBS, noise, draught) some European countries do not recommend full air-conditioning and sometimes even prohibit it.

Alternatively, heating and cooling may be done by water-based radiant heating and cooling systems, where pipes are embedded in the building structure (floors, ceilings, walls) or in the centre of the concrete slabs in multi-storey buildings. The present paper will discuss the possibilities and limitations of radiant surface heating and cooling systems. Differences in performance and application of surface systems compared to embedded systems are presented. Results from both dynamic computer simulations and field measurements are presented.

The paper shows that for well designed buildings these types of system are capable of providing a comfortable indoor climate both in summer and in winter in different climatic zones. Various control concepts and corresponding energy performance are presented.

To remove latent heat, these systems may be combined with an air system. This air system can, however, be scaled down with the benefit of improved comfort (noise, draught) compared to full air-conditioning. An added benefit can be reduced building height due to the elimination of suspended ceilings. Finally, surface heating and cooling systems use water at a temperature close to room temperature. This increases the possibility of using renewable energy sources and increasing the efficiency of boilers, heat pumps and refrigeration machines

1. INTRODUCTION

In Europe it is mainly water-based heating systems that are used. These systems use radiators or floor heating as heat emitters. One advantage compared with air systems is the more efficient means of transporting energy. The demand for comfort, better insulation of buildings, and greater internal loads from people and equipment have increased interest in installing also a cooling system to keep indoor temperatures within the comfort range. This resulted first of all in the introduction of suspended ceiling panels for cooling and in recent years also in the use of floor systems for cooling (Holst and Simmonds, 1999; Olesen, 1997; Simmonds, 1994; Børresen, 1994). Typical positioning of pipes for wall, floor and ceiling systems is shown in Figure 1.

A new trend, which 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. Pipes carrying water for heating and cooling are embedded in the centre of the concrete slab (Figure 1).

By activating the building mass, you will not only get a direct heating-cooling effect, but you will also, due to the thermal mass, reduce the peak load and transfer some of the load

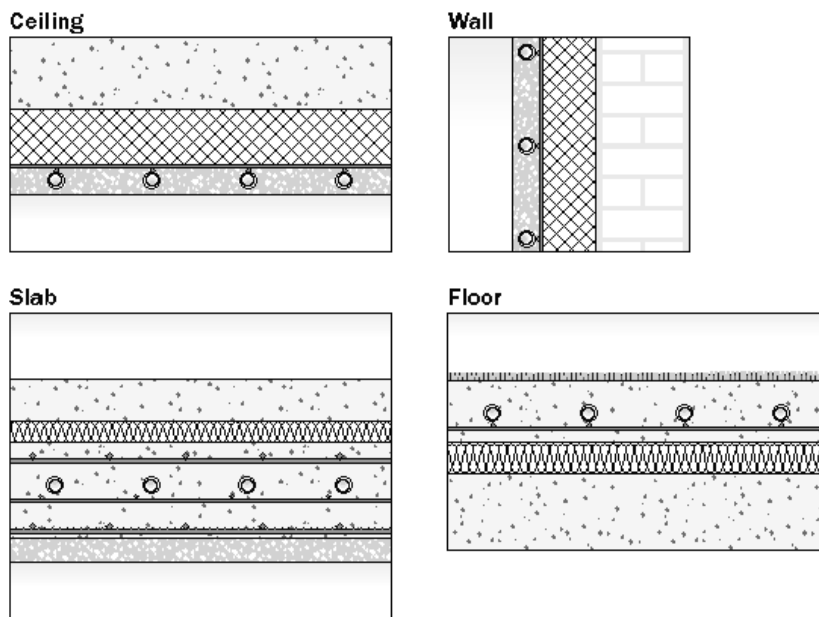


Figure 1. Examples of the positioning of pipes in floor, wall, ceiling and slab constructions.

outside the period of occupancy. Because these systems for cooling operate at a water temperature close to room temperature, they increase the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources. The present paper will discuss the possibilities and limitations of radiant heating and cooling systems. Especially results from studies on systems where pipes are embedded in the concrete slab between each storey of a building are presented. These results are based on dynamic computer simulation and measurements in buildings during normal operation.

2. THERMAL COMFORT

The requirements for thermal comfort may limit the capacity and use of radiant surface heating and cooling systems. Based on international standards and guidelines (ISO, 1993; CEN, 1998), the thermal comfort requirements for people with mainly sedentary activity (1.2 met) is in winter (heating season, 1.0 clo) an operative temperature range of 20-24°C and in summer (cooling season, 0.5 clo) 23-26°C. In CR 1752, different classes of thermal environment may be specified. A higher class has an operative temperature range of 23.5-25.5°C and a lower class a range of 22-27°C. In the German Standard DIN 1946 (DIN 1944, 1994) the operative temperature may increase up to 27°C and for higher outdoor temperatures up to 32°C. Especially for high thermal mass systems it is important that comfort is specified as a range because with these systems the room temperature cannot be controlled at a fixed level.

As the heat transfer between the heated or cooled surfaces, the space and people in the space is mainly by radiation, it is important to use the operative temperature for specifying comfort conditions and for load calculations. With concrete slab systems, where the dynamic effects

and thermal storage capacity of the slabs are used, the operative temperature during the day should be within the comfort range. Studies by Knudsen et al. (1989) show that as long as the temperature change is less than 5 K per hour, the temperature range based on steady-state conditions (ISO 7730) is still valid.

Compared to air systems, there will be fewer problems with draught and noise using water-based, slab heating and cooling systems.

Further comfort requirements are related to vertical air temperature differences, radiant temperature asymmetry, and too high or low surface temperatures. Measurements with floor cooling (Olesen, 1997) show that even at a floor temperature of 10 K lower than the room temperature, the vertical air temperature difference between head and feet is less than the required 3 K. The comfort requirements for radiant temperature asymmetry due to a heated ceiling is 5 K and for a cooled ceiling 14 K. This will limit the acceptable ceiling temperature for heating to approximately 27-28 °C. For a cooled ceiling, the dew point in the space and not the radiant asymmetry will limit the lower surface temperature. The acceptable range for the floor temperature for people wearing shoes is 19-29°C. However, in spaces where people are mainly involved in sedentary activity, it is recommended that the floor temperature be no less than 20°C.

3. HEATING AND COOLING CAPACITY

The important factors for the heating and cooling capacity of surface systems are the heat exchange coefficient between the surface and the room, the acceptable minimum and maximum surface temperatures based on comfort and consideration of the dew point in the space and heat transfer between the pipes and the surface (Table 1)

Table 1. Heat exchange coefficient, minimum and maximum recommended surface temperature and cooling and heating capacity (Olesen, 1997, Olesen, 2000).

		Total heat exchange coefficient W/m ² K		Surface temperature °C		Capacity W/m ²	
		Heating	Cooling	Maximum	Minimum	Heating	Cooling
Floor	Perimeter	11	7	35	20	165	42
	Occupied zone	11	7	29	20	99	42
Wall		8	8	~40	17	160	72
Ceiling		6	11	~27	17	42	99

The heat exchange coefficient depends on the position of the surface and the surface temperature in relation to the room temperature (heating or cooling). While the radiant heat exchange coefficient is for all cases approximately 5.5 W/m²K, the convective heat exchange coefficient will change. The listed maximum surface temperature for the floor is based on the European standard for floor heating (EN 1264,), where it is permitted in the perimeter zone 1 m from outside walls, to increase the maximum floor temperature to 35 °C. The maximum temperature for the wall is based on the pain limit for skin temperature, approximately 42 °C, and the risk of being in contact with the wall over a longer period of time. The maximum temperature of the ceiling is based on the requirement to avoid temperature asymmetry. The minimum surface temperatures for wall and ceiling are based on consideration of the dew point and risk of condensation.

A special case for floor cooling is when there is direct sun radiation on the floor. In this case the cooling capacity of the floor may exceed 100 W/m² (Børresen, 1994). This is also why

floor cooling is increasingly used in spaces with large glass surfaces like airports (Simmonds et. al. 2000), atriums and entrance halls.

The heat transfer between the embedded pipes and the surface of wall, ceiling or floor will, as long as there is no airspace in the construction, follow the same physics. It is then possible for all three type of surface to use the standard for floor heating (CEN, 1998) as the basis for design and calculation of the direct heating and cooling capacity, depending on the distance between pipes, the thickness above (below) pipes, the surface material and the water temperature. The heat exchange coefficient depends, however, on the position of surfaces (wall, ceiling, floor) and whether heating or cooling is used (Olesen, 1997, Olesen et. al., 2000).

The heating and cooling capacities mentioned above are for systems where the pipes are positioned near the surface of ceiling or floor. This will require water temperatures within the range 15-45°C, depending on the construction of ceilings and floors.

If the humidity is not controlled, the cooling capacity may be further reduced. To obtain the same capacities with the pipes embedded in the centre of the concrete slabs, an even wider water temperature range would be needed. This would, however, make it almost impossible to control the system. Therefore much lower capacities are possible with concrete slab systems.

It is therefore recommended to use these systems only if the loads are less than 50 W/m².

In office buildings it is very common to use a raised floor for running cables. In the case of concrete slab cooling, most of the heat transfer will then be over the ceiling side, which means suspended ceilings should not be used. As the air systems only have to be sized for the ventilation rate needed for acceptable indoor air quality, which means an air change rate of 1 to 2 h⁻¹ instead of 4 to 6 h⁻¹, the ducts will be much smaller and a suspended ceiling is not needed. The air ducts and the main supply and return water pipes are then installed in the hallway between the offices. The avoidance of suspended ceilings has the big advantage of reducing the total building height, resulting in significant savings on construction costs and materials used. Without the suspended ceiling the acoustical requirements must be solved in other ways.

4. OPERATION AND CONTROL

Even if surface heating and cooling systems often have a higher thermal mass than other heating/cooling systems, they have a high control performance. This is partly due to the small temperature difference between the room and the system (water, surface) and the resulting high degree of self-control. Studies on controllability of floor heating/cooling (Olesen, 2001) show that floor heating control the room temperature as well as radiators. To avoid condensation on a cooled surface, there is a need to include a limitation on water temperature, based on the space dew-point temperature.

If, however, the pipes are embedded in the building structure, it is often questioned how these systems should be controlled or operated. Some studies deal with this issue (Brunello et.al., 2000, Carli de et. al., 2001; Olesen, 2002). In the following, further results are presented.

A 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).

4.1 Description of system and test space

The system considered is shown in Figures 2 and 3. 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. 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 2.

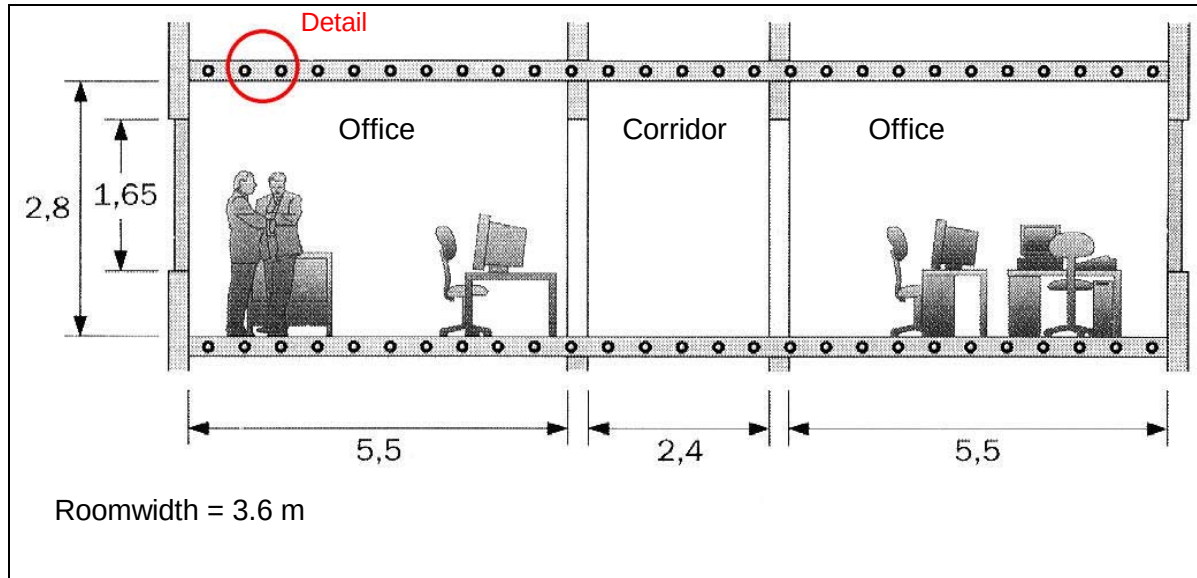


Figure 2. Central room module used for the computer simulation of a building with concrete slab cooling. All dimensions are in metres.

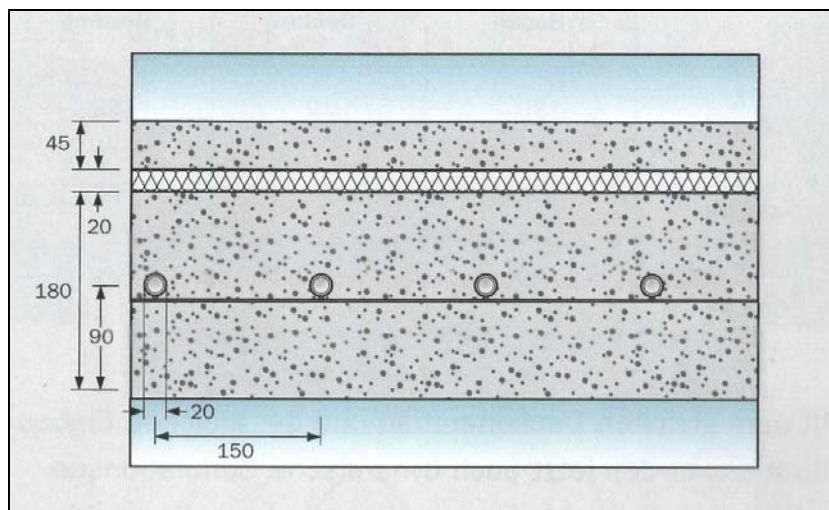


Figure 3. Position of the plastic pipes in the concrete slab between two storeys.

The floor (Figure 2) consists of 45 mm screed ($\lambda = 1.4 \text{ W/m}^2\text{K}$, $c = 1 \text{ kJ/kgK}$, $\rho = 2000 \text{ kg/m}^3$), 20 mm insulation ($\lambda = 0.04 \text{ W/m}^2\text{K}$, $c = 1.5 \text{ kJ/kgK}$, $\rho = 50 \text{ kg/m}^3$) and

180 mm concrete ($\lambda = 2.1 \text{ W/m}^2\text{K}$, $c = 1 \text{ kJ/kgK}$, $\rho = 2400 \text{ kg/m}^3$). The outside pipe diameter is 20 mm and the spacing is 150 mm. The window has a U-value = $1.4 \text{ W/m}^2\text{K}$. The room volume is 55.44 m^3 with a thermal capacity of 700 kJ/K .

4.2 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.

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

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} ($\sim 11 \text{ l/s}$ per person).

Sun protection: during occupation, by direct exposure of sunlight and operative temperature above 23°C , reduction factor $z = 0.5$.

4.3 Control parameters studied

Three control parameters were studied:

- Control of water temperature
- Dead-band for room temperature
- Use of weather forecast

4.3.1 Control of water temperature

The goal for the system used in the present study was 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 ($\frac{1}{2}(t_{\text{return}} - t_{\text{supply}})$) 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:

$$t_{\text{supply}} = 0,52 * (20 - t_{\text{external}}) + 20 - 1,6 * (t_{\text{operative}} - 22) \text{ } ^\circ\text{C} \quad (\text{case 801})$$

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

$$t_{\text{average}} = 0,52 * (20 - t_{\text{external}}) + 20 - 1,6 * (t_{\text{operative}} - 22) \text{ } ^\circ\text{C} \quad (\text{case 901})$$

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:

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

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

4.3.2 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)

4.3.3 Use of weather forecast

As the reaction time of the 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	$T_{sup} = 0.5 \cdot (18 - t_{ex}) + 18$	mean value next 24 hours	21.5-23.5
19	$T_{sup} = 0.5 \cdot (18 - t_{ex}) + 18$	mean value next 72 hours	21.5-23.5
20	$T_{sup} = 0.5 \cdot (18 - t_{ex}) + 18$	mean value 12 hours around actual time	21.5-23.5
21	$T_{sup} = 0.5 \cdot (18 - t_{ex}) + 18$	mean value 24 hours around actual time	21.5-23.5
24	$T_{sup} = 0.5 \cdot (18 - t_{ex}) + 18$	instant value	21.5-23.5

5. 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 23-26°C recommended for summer (cooling period) and 20-24°C recommended for winter (heating period) (ASHRAE, 1992; CEN, 1998; ISO, 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.

5.1 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.

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 of 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 for the other cases.

In the summer, case 1401 is overall better than the others. Due to the warmer climate in Venice (Table 3) the room temperatures are higher, and energy use and pump running time are also higher compared to Würzburg.

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 from 17:00 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 = F = 22°C 1201	Average = F (outside) 1401	Supply = F (outside) 0801	Average = F (outside) 0901	Average = F = 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 from 17:00 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 6) 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

5.2 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 7 and for the winter period in Table 8. 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°

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). 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

Conclusions of the dead-band analysis. By optimizing 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 greater than 2 K.

5.3 Study on use of 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.

Table 8: 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	21-23 °C	21-24 °C	22-23 °C	21-23 °C	21-24 °C
		0901-1	0901-8	0901-9	0901-1	0901-8	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

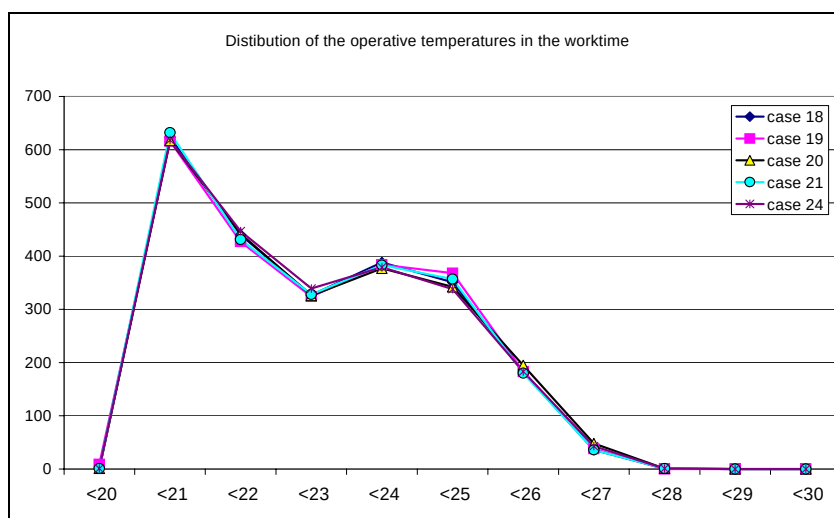


Figure 4. Distribution of operative temperature during working time.

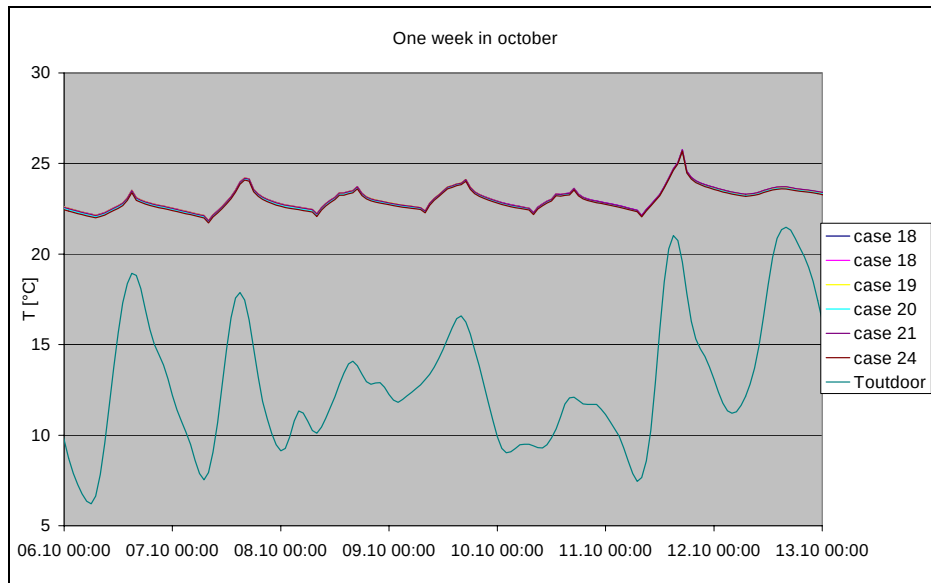


Figure 5. Operative temperature during a week in October.

6. FIELD MEASUREMENTS

Hundreds of buildings exist with embedded heating/cooling systems. To study the performance in real buildings, some field measurements of thermal comfort conditions were made in several buildings with radiant surface systems: floor, wall and systems with pipes embedded in the concrete slabs between each floor in a multi-storey building (de Carli and Olesen, 2001). Long-term measurements of operative, air, surface, system and external temperatures have been carried out. The results from one of the buildings are given below.

In this building, an active thermal slab system of 6500 m² was installed for heating and cooling. The building had raised floors for the installation of cables, but only a limited area with suspended ceiling and openable windows. Mechanical ventilation was provided by a displacement system, the supply air being pre-cooled or heated to a temperature 1-3 degrees below room temperature.

Measurements have been made in two open-space offices on the 4th and 5th floors during August 1999, from mid June to mid October 2000, and from December 2000 to January 2001. The outside temperature was also measured. The water supply temperatures were controlled in the range 19-23°C from summer to winter according to the outside temperature.

The system was in operation only from 18:00 until 10:00.

Cooling period. A sample of operative temperature can be seen in Figure 6 for a typical warm working week. From Table 9 it appears that for 95% of the total working time operative temperatures are between 21°C and 26°C. From the tables it can be seen that temperatures on the 5th floor are higher than those on the 4th floor. This is because the two floors are connected by an open stairway in the middle of the landscape offices. Therefore, some of the convective part of the internal loads on the 4th floor (people, equipment, sun) will rise to the 5th floor and increase the internal load there.

It can be seen that on some days the temperature in the morning is on the cool side. As no subjective evaluations were made, it is impossible to determine whether this caused a real

comfort problem or not. The low temperatures could probably be avoided by decreasing the number of hours of cooling operation during the night.

Heating period. A example of the operative temperature can be seen in Figure 7 for a typical working week under heating conditions. From Table 10 it can be seen that the operative temperatures are, for most of the time, within the comfort range suggested by the existing standards. Except for the 4th floor south, the measured operative temperatures are within the recommended comfort range; in this position 11% of the time the temperature dropped below 20°C. The building had an additional heating system installed which, however, has not been in operation. The basic heating is made by the activated concrete slab system. During the winter, however, the supply air temperature increased above the room temperature during the morning hours. After 1-2 hours' occupancy, the supply temperature again decreased below room temperature.

Table 9. Percentage of operative temperature distribution during working time (cooling period)

Temperature range [°C]	4 th floor window east	4 th floor window south	5 th floor window west	5 th floor window east	5 th floor middle	meeting room	all offices except middle
<20	0.0	1.2	0.0	0.0	0.0	0.0	0.2
20-22	11.2	34.5	2.5	1.4	20.4	35.7	17.1
22-25	88.6	64.4	75.0	71.7	72.6	63.8	72.7
25-26	0.1	0.0	18.4	21.7	7.0	0.5	8.1
26-27	0.0	0.0	3.7	5.2	0.0	0.0	1.8
>27	0.0	0.0	0.4	0.0	0.0	0.0	0.1

Table 10. Percentage of operative temperature distribution during working time (heating period).

Temperature change during a day [°C]	4 th floor window east	4 th floor window south	5 th floor window west	5 th floor window east	meeting room	all offices
<20	0	11	0.1	0	0	2.2
20-22	55.3	75.1	34	18.1	29.9	42.5
22-25	44.7	13.9	65.9	81.9	70.1	55.3
>25	0	0	0	0	0	0

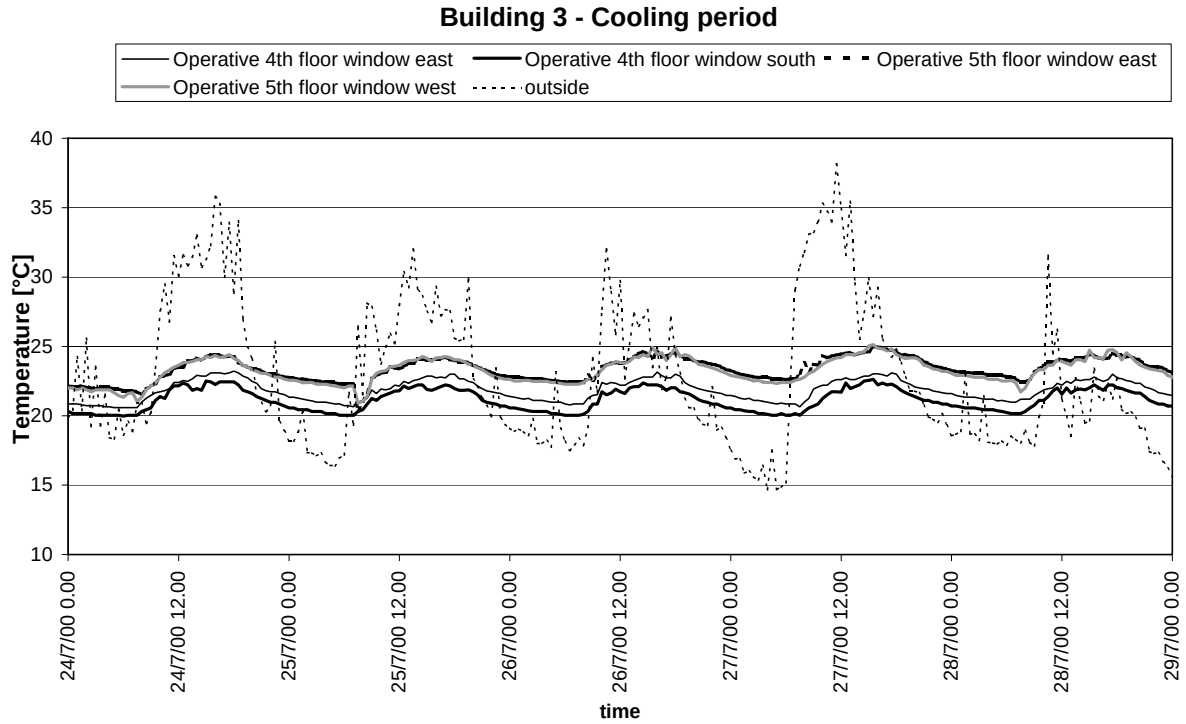


Figure 6 – Sample of temperature trend in a working week for cooling conditions in Building 3

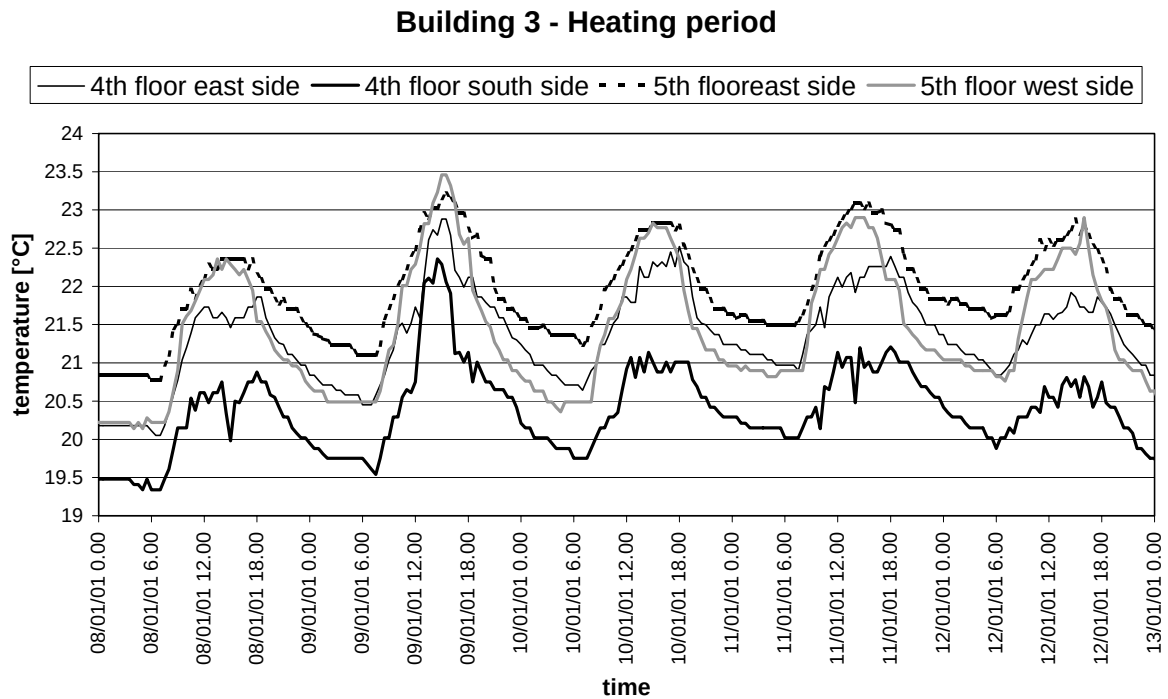


Figure 7. Sample of temperature trend in a working week for heating conditions in Building 3

6. CONCLUSIONS

The use of surface heating and cooling using water based systems is becoming very popular. Procedures for calculating the steady-state heating/cooling capacity are available.

By a proper control the risk for condensation on the cooled surfaces can be limited.

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.

Due to the use of water temperatures close to room temperatures water based surface heating and cooling systems will increase the possibility to use renewable energy sources like ground source heat pumps, ground heat exchangers, geothermal energy, solar energy, evaporative cooling etc.

The level of water temperatures used also increase the efficiency of boilers, chillers and heat pumps.

7. REFERENCES

ASHRAE 55. 1992. Thermal Environmental Conditions for Human Occupancy, Atlanta, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc

Brunello, P., Di Gennaro, G., De Carli, M., Zecchin, R. 2001. Mathematical modeling of radiant heating and cooling with massive thermal slab. Proceedings of Clima 2000, Naples.

Børresen, B. (1994). Fußbodenheizung und -Kühlung von Atrien, 16. Internationaler Velta-Kongreß, St. Christoph/Tirol.

Carli, M. de, Peron, F., Romagnoni, P., Zecchin, R. (2000). Computer simulation of ceiling radiant heating and cooling panels and comfort evaluation. Proceedings of Healthy Buildings, Helsinki.

Carli, M. de, Olesen, B.W. (2001). Field measurements of thermal comfort conditions in buildings with radiant surface cooling systems. Proceedings of Clima 2000, Naples.

CEN (199) Ventilation for Buildings: Design Criteria for the Indoor Environment, Brussels, European Committee for Standardization (CR 1752).

DIN. 1994. DIN 1946-1994, Raumluftechnik Teil 2. Berlin: Deutsches Institut für Normung.

EN1264 (1998), Floor heating, Systems and components.

Fort, K. 1996. Type 160: Floor Heating and Hypocaust.

Hauser, G., Kempkes, Ch., Olesen, B. W. (2000), Computer Simulation of the Performance of a Hydronic Heating and Cooling System with Pipes Embedded into the Concrete Slab between Each Floor. ASHRAE Winter meeting, Dallas, 5-9 February 2000.

Holst, S. and Simmonds, P., (1999), Kühlkonzeption am Beispiel Flughafen Bangkok, 21. Internationaler Velta-Kongreß, St. Christoph/Tirol

International Organization for Standardization (1993) Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specification of the Conditions for Thermal Comfort (EN ISO Standard 7730).

Knudsen, H. N. et. al. (1989), Thermal Comfort in Passive Solar Buildings. Technical University of Denmark.

Koschenz M. and Dorer V. (1996), Design of air systems with concrete slab cooling. 5th International Conference on Air Distribution in Rooms, Roomvent '96.

Koschenz M. (1998), Thermoaktive Bauteilsysteme. Potentialabschätzung und Erfahrungen. Beitrag am 10. CH-Status-Seminar ETHZ, 10-09-98, Zürich.

Meierhans, R.A. and Olesen, B. W. (1999), Betonkernaktivierung, Book, 67 pg. ISBN 3-00-004092-7

Meierhans, R.A. (1993) Slab cooling and earth coupling, ASHRAE Transactions, V. 99, Pt 2.

Meierhans, R.A. (1996) Room air conditioning by means of overnight cooling of the concrete ceiling. ASHRAE Transactions, V. 102, Pt. 2.

Olesen, B.W. (1997, Possibilities and limitations of radiant floor cooling, ASHRAE Transactions. V.103, Pt.1.

Olesen, B.W., Michel, E., Bonnefoi, F., De Carli, M. (2000) Heat exchange coefficient between floor surface and space by floor cooling: theory or a question of definition, ASHRAE Transactions, Part I.

Olesen, B.W. (2001) Control of floor heating and cooling systems“ . Clima 2000/Napoli 2001 World Congress – Napoli, September 2001.

Olesen, B.W. (2002) Control of slab heating and cooling systems studied by dynamic computer simulations, AICARR conference, Milan, 2002.

Simmonds, P., Gaw, W., Holst, S., Reuss, S. (2000) Using radiant cooled floors to condition large spaces and maintain comfort conditions, ASHRAE Transactions, Part I.

Simmonds, P. (1994) Control strategies for combined radiant heating and cooling systems, ASHRAE Transactions, v. 100, Pt. 1.

Steimle (1999) Entwicklung der Wärmepumpentechnik – der Fußboden als Heiz- und Kühlfläche -. 21. Internationaler Velta-Kongreß, St. Christoph/Tirol.

TRNSYS (1998) TRNSYS 14.2 - User's Manual.