COOLING AND HEATING OF BUILDINGS BY ACTIVATING THEIR THERMAL MASS WITH EMBEDDED HYDRONIC PIPE SYSTEMS -

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Summary

Due to intensive use of energy and high costs in several European countries it is often debated if air-conditioning of buildings is recommendable or should be prohibited by law. Of course, air-conditioning will give better control of the indoor temperature and then improve comfort and productivity. But there also exist many examples of discomfort in air-conditioned buildings due to draught, noise and sick building syndrome. By air-conditioning, heating, cooling and ventilation are achieved alone by air, where the cooling and heating requirements determine the amount of required air circulation. Alternatively, the heating and sensible component of cooling may be done by hydronic radiant heating and cooling systems, where pipes are embedded in concrete slabs between each storey. The system may be combined with a ventilation system, where the amount of outside air is based on the requirements for acceptable are quality. This paper discusses the possibilities and limitations of such heating and cooling systems, and examples of buildings having this type of systems are presented.

INTRODUCTION

In Europe mainly hydronic heating systems 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 from the central plant to the space. The demand for comfort, better insulation of buildings, and increased internal loads from people and equipment has increased interest in also installing 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, 1997a, 1997b, Simmonds, 1994, Børresen, 1994). Typical positioning of pipes for wall, floor and ceiling systems are shown in **Figure 1**.

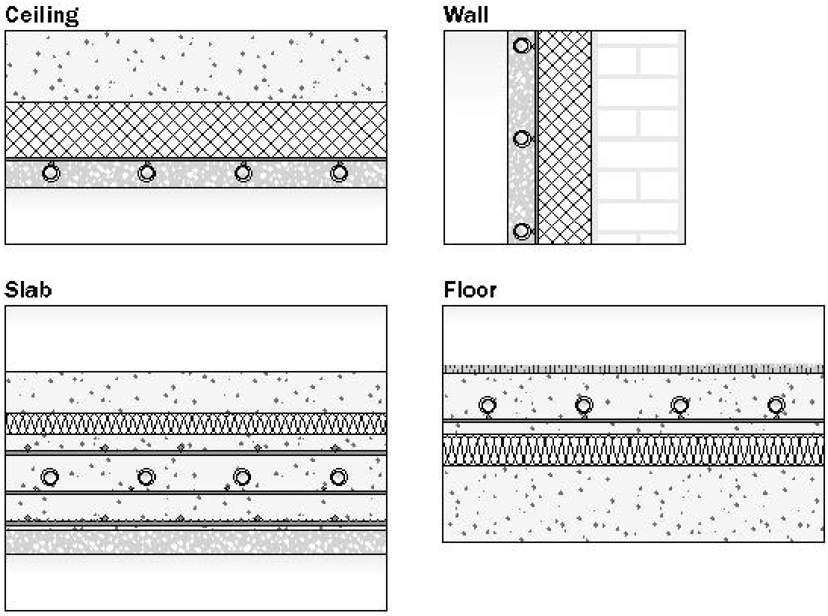

Figure 1: *Examples of the positioning of pipes in floor, wall, ceiling and slab constructions.*

A new trend, which started in the early nineties in Switzerland (Meierhans, 1993 and 1996), involves the use of 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 thermal mass one will not only get a direct heating-cooling effect, but one will also reduce the peak load and transfer some of the load to the period of non-occupancy. Because these systems for cooling operate at water temperature close to room temperature, they increase the efficiency of heat pumps, ground heat exchangers and other systems using renewable energy sources.

THERMAL COMFORT

Thermal comfort requirements may limit the capacity and use of radiant surface heating and cooling systems. According to international standards and guidelines (ISO7730, 1994, CR1752, 1998) the thermal comfort requirements in winter (heating season) for people with mainly sedentary activity (1.2 met, 1.0 clo), the operative temperature range is between 20 and 24 °C. In summer (cooling season, 0.5 clo) it is between 23 and 26 °C. These requirements are very similar to ASHRAE 55-92 (1992). The CIBSE Guide A (CIBSE, 1999) for offices recommends a 22-24°C temperature range for summer. This is, however, based on a criteria for PMV ± 0.25, while the ISO and CEN range is based on PMV ± 0.5. In CR 1752 different classes of thermal environment may be specified. A higher class has an operative temperature range 23.5 to 25.5 °C and a lower class a range 22-27 °C. In the German Standard DIN 1946 (DIN 1946, 1994) the operative temperature may increase up to 27 °C for higher outside temperatures up to 32 °C. Especially for high thermal mass systems it is important that comfort is specified in a range because with these systems the room temperature cannot be controlled at a fixed value:

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 should during the day ramp inside the comfort range. Studies by Knudsen et. al. (1989) show that as long as the temperature change is less than 0,55 K per hour the temperature range based on steady state conditions (ISO 7730) is still valid.

Compared to forced air-systems there will due to less air movements be less problems with draught and noise using hydronic, slab heating and cooling systems.

HEATING AND COOLING CAPACITY

Important factors for the heating and cooling capacity of hydronic systems embedded in concrete slabs are the heat exchange coefficient between the slab surface and the indoor space, the acceptable minimum and maximum slab surface temperatures based on comfort, consideration of the dew point in the space, and heat transfer between the pipes and the surface. Total heat exchange coefficients (convection + radiation) are listed in **Table 1**.

Table 1: *Total heat exchange coefficient (convection + radiation) between surface and space for heating and cooling, acceptable surface temperatures and capacity by 20 °C room temperature for heating and 26 °C room temperature for cooling (Olesen, 1997 b, Olesen et. al. 2000).*

		Total heat exchange coefficient W/m^2.K		Acceptable surface temperature °C		Maximum capacity W/m^2	
		Heating	Cooling	Max. Heating	Min. Cooling	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, Olesen 1997b, 2000). While the radiant heat exchange coefficient is for all cases approximately 5.5 W/m^{2}K, the convective heat exchange coefficient will change. The heating-cooling capacity depends on the heat exchange coefficient and the temperature difference between surface and space. Acceptable surface temperature is determined based on comfort considerations and the risk for condensation (Table 1, Olesen 1997 b). For sensible cooling the ceiling has a capacity up to 100 W/m^2 and for heating 40 to 50 W/m^2. A floor has the highest capacity for heating, up to 100 W/m^2, and 40 W/m^2 for sensible cooling. A special case for floor cooling is when there is direct sun radiation on the floor. In this case the sensible cooling capacity of the floor may exceed 100 W/m^2 (Børresen, 1994). This is also why floor cooling is increasingly used in spaces with large fenestration 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 for heat conduction. It is then possible for all three type of surfaces to use the standard for floor heating (EN1264, 1998) as the basis for design and calculation of the direct heating and sensible cooling capacity depending on the spacing between pipes, thickness above (below) pipes, surface material and water temperature. The heat exchange coefficient depends, however, on the location of surface (wall, ceiling, floor) and if heating or cooling is used (Olesen, 1997a, 1997 b, Olesen et. al 2000).

The heating and sensible 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 to 45 °C depending on the construction of ceilings and floors. If the humidity is not controlled, the cooling capacity may be further reduced in order to avoid surface condensations. 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 because of the much greater thermal mass. Therefore much lower capacities should be used when designing concrete slab systems.

It is therefore only recommended to use these systems 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. A mechanical ventilation system only has to be sized for the ventilation rate needed for acceptable indoor air quality, which in offices 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.

COMPUTER SIMULATIONS

Besides the direct cooling and/or heating capacity as discussed above for a surface system the effect of the thermal storage in the concrete slabs must be considered. This dynamic effect is more difficult to calculate and computer simulation is often required. By a simple simulation program the effect of a slab cooling system is demonstrated in **Figure 2 (**Meierhans and Olesen, 1999**)**.

The upper part of **Figure 2** shows the temperature variation over 24 hours for a space exposed to an internal load and without any cooling. At the initial state 6:00 hour in the morning all surface temperatures are 20 °C. Just after the internal load is present an immediate rise in the room temperatures occurs. The operative temperature keeps increasing the whole day to approximately 26 ^{o}C at 18:00 hour, when the internal load decline. During the night, without internal loads, the space cools down and reaches by the next morning an operative and average slab temperature of 21.3 ^{o}C, which is 1.3 K higher than the day before. Each day the temperatures will then increase progressively. If instead, as shown in the centre part of **Figure 2**, the core of the concrete slab is kept at 20 ^{o}C all the temperatures will, the next morning, come back to the same level as the day before. During the day the average slab temperature increases to 21.5 ^{o}C, but it is cooled down again during the night. The lower part of **Figure 2** shows the temperatures when the core is only cooled to 20 ^{o}C when the building is unoccupied . The results are almost the same as for the 24 hour cooling. The operative temperature is only slightly higher. The reason is that during the period when the core is kept at 20 ^{o}C, the temperature difference between core and average slab is higher, which results in an increased energy transport. So even if the "cooling" time is less, the total cooling effect is about the same as for 24 hour cooling.

This shows one of the benefits of using the concrete slab as thermal storage. The peak load during the day will be stored and removed by cooling during the night. This will lead to a downsizing of the cooling equipment and use of cheaper electricity during night time for refrigeration machines.

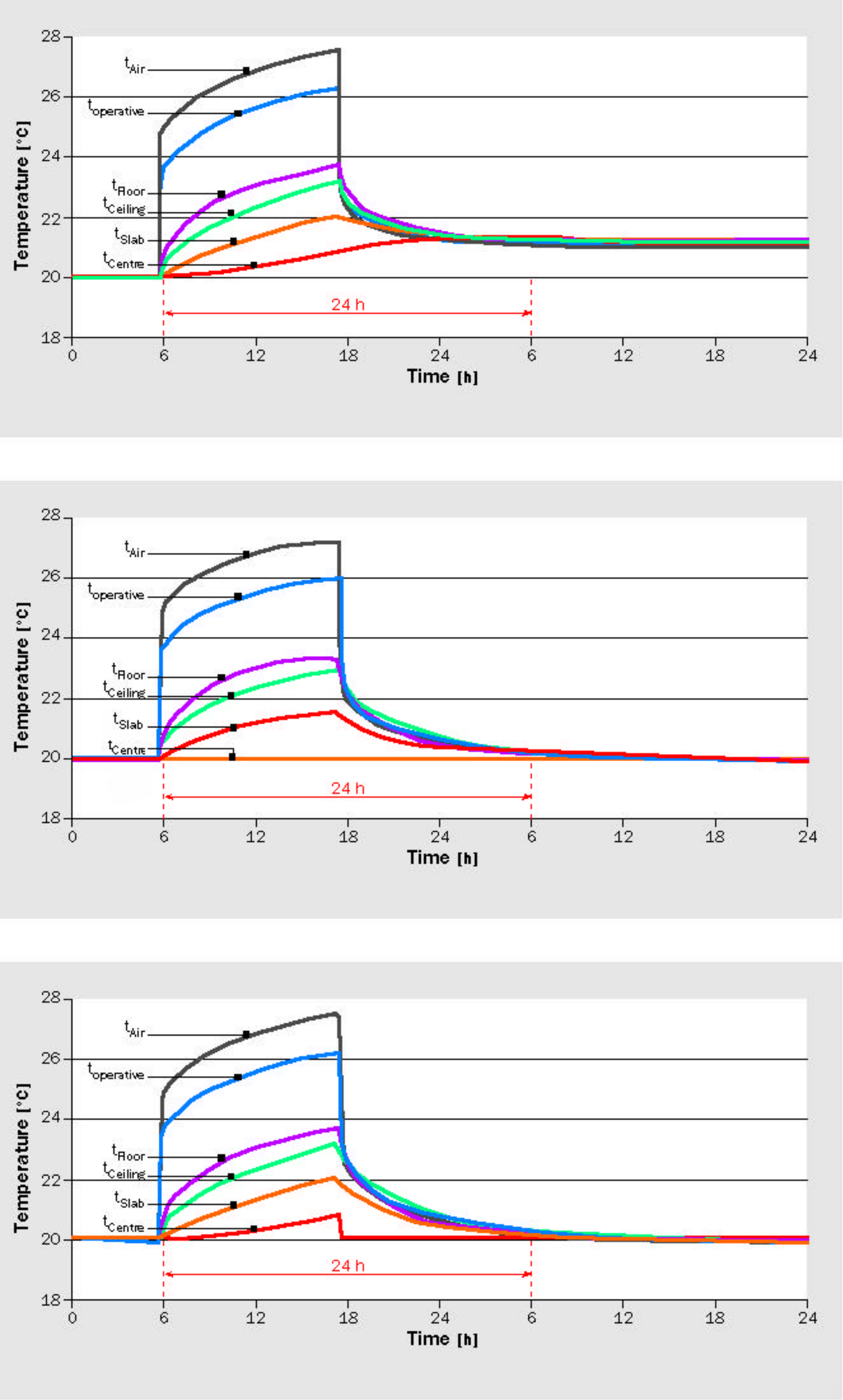

Figure 2: *Calculated air-, operative-, floor-, ceiling-, average slab- and slab core temperatures for a space with a constant internal load of 90 W/m^2 from persons, light, sun etc. Upper part without cooling, middle part with constant core (water) temperature of 20 ^{o}C and lower part with cooling only outside the time of occupancy (Meierhans and Olesen, 1999).*

The above system is often combined with an air system, which is now dimensioned only to provide the amount of air needed for an acceptable air quality. During the day the cooling equipment is used for pre-conditioning of the ventilation air and during the night for cooling the concrete slabs. As a result the cooling equipment can be down-sized.

Normally more sophisticated computer simulations must be used to evaluate the dynamic performance of building and system. (Hauser et. al. 2000, Koschenz 1996, 1998, Meierhans and Olesen, 1999, Meierhans, 1993). The whole building is not simulated, but a typical room assumed to be surrounded by rooms with similar conditions is used for the simulation. Such an example is shown in **Figure 3**.

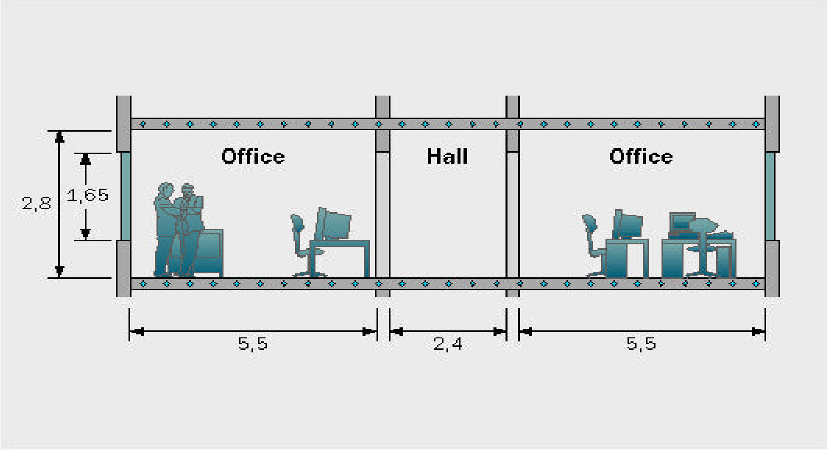

Figure 3: *Central room module used for the computer simulation of a building with concrete slab cooling. All dimensions are in meter.*

A reference year for Würzburg in Germany was used for the outdoor climate. The office was assumed to be occupied Monday to Friday between 8:00 to 17:00 hour. Internal loads from persons and equipment was set to 28 W/ m^2 . Air change rates were 0.3 h^{-1} for non-occupancy, 0.8 h^{-1} for occupancy, and 5.0 h^{-1}, when the operative temperature exceeded 24 ^{o}C. External sun screen (factor 0.5) was in operation during the hours of occupancy when operative temperatures were higher than 23 ^{o}C. Further building details may be found in Hauser et. al. (2000).

The building as described in **Figure 3** was simulated without any cooling, with slab cooling for all 24 hours and with slab cooling only during the time of occupancy, 9 hours. The supply water temperature for the slab cooling was always controlled at the dew point temperature in the space. In this way the surface temperature at the slab was always higher than the dew point.

Figure 4 is showing the number of hours, where the operative temperature is exceeding a given value.

The results are also shown in **Table 2** as the number of "degree hours", where an operative temperature of 26 ^{o}C is exceeded. (Degree hours = $\sum (t_{operative} - 26\ ^{o}C) x$ hours).

This example shows a very significant improvement (less hours above the comfort range) of the thermal comfort using a slab cooling system compared to no cooling system.

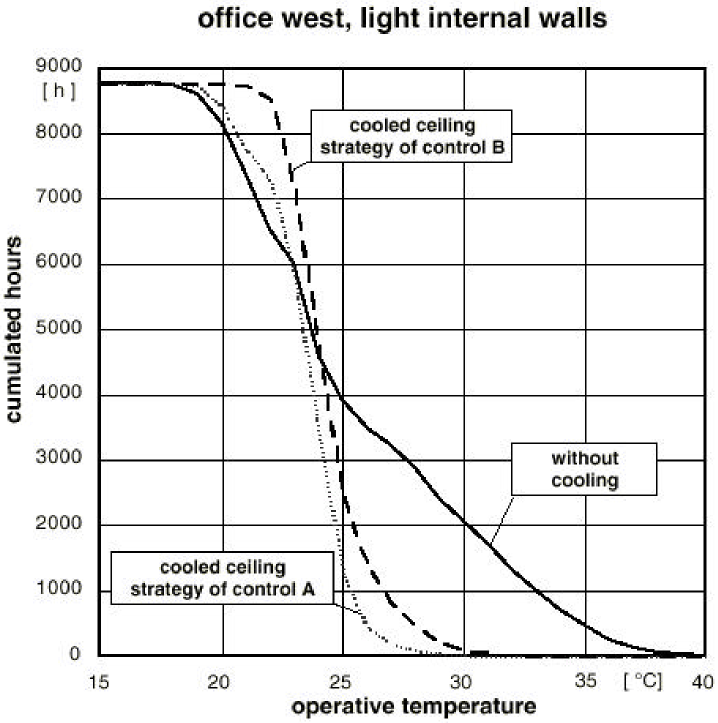

Figure 4: *Cumulative number of hours where the operative temperature exceeds a certain value for no cooling, 24 h cooling (Strategy A) and 9 h cooling (Strategy B).*

Table 2: *Results of a computer simulation in "Degree Hours", where an operative temperature of 26 ^{o}C is exceeded. The calculations were made for different room types and orientations(Hauser et. al. 2000) .*

		West, Light ^{o}C xhours	East, Light ^{o}C xhours	West, Heavy ^{o}C xhours	East, Heavy ^{o}C xhours
Total time	No cooling	14600	16400	13600	14800
	24h cooling	360	400	0	0
	9h cooling	1320	1600	560	800
Time of occupancy	No cooling	3200	4000	3000	3600
	24h cooling	0	0	0	0
	9h cooling	360	520	160	360

EXAMPLES OF BUILDINGS

In this section some of existing buildings with pipes embedded in the concrete slabs between each floor for heating and cooling will be described.

Office building in Munich

A model picture of the building is shown in **Figure 5** and the main building data are given in **Table 3**. The slab heating and cooling system was combined with a mechanical ventilation system and radiators as an additional heating system (**Figure 6**). The four storey building consists of two main long parallel buildings, each with additional building wings (**Figure 5**). The building has offices facing north, south, east and west. The facades exposed to sunshine have an external sun shading (**Figure 6**). In almost all areas there are operable windows. In a couple of spaces (conference rooms) with higher internal loads a suspended cooled ceiling was installed (**Figure 6**). The building was divided in four zones with separate supply-return pipes and control, so they independently could be cooled or heated. The design water temperatures were for cooling 16 °C supply/19 °C return and 24 °C supply/22 °C return for heating. The supply temperature was controlled separately for each zone according to an average zone temperature based on several room temperature sensors. For this building several computer simulations were made and an example is shown in **Figure 7**.

Table 3: *Data for an office building in Munich*

Building	
Floors	4
Floor area (offices, conference, cantina)	42.000 m^2
Thickness concrete slabs	28 cm
Operable windows	
In operation	1999
Ventilation	
Exhaust	120.000 m^3/h
Ventilation	35.000 m^3/h
Air Conditioning	63.200 m^3/h
Heating and Cooling	
Heating load, radiators	950 kW
Heating load, ventilation	765 kW
Cooling load	630 kW
Concrete slab cooling	13.500 m^2
Estimated energy costs	8,80 DM $m^2 \cdot a$

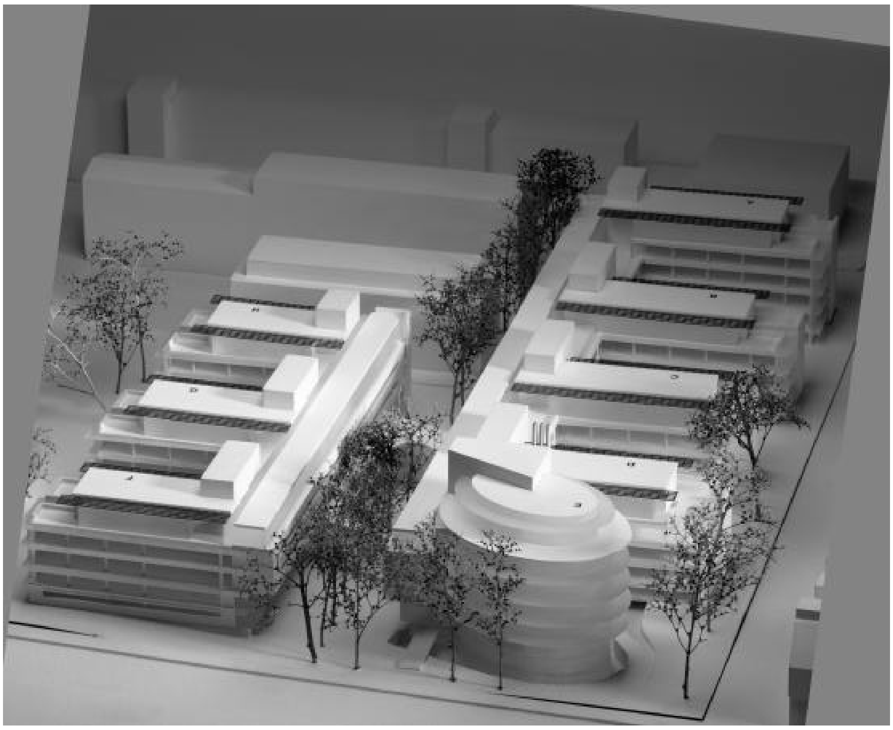

Figure 5: *Office building in Munich*

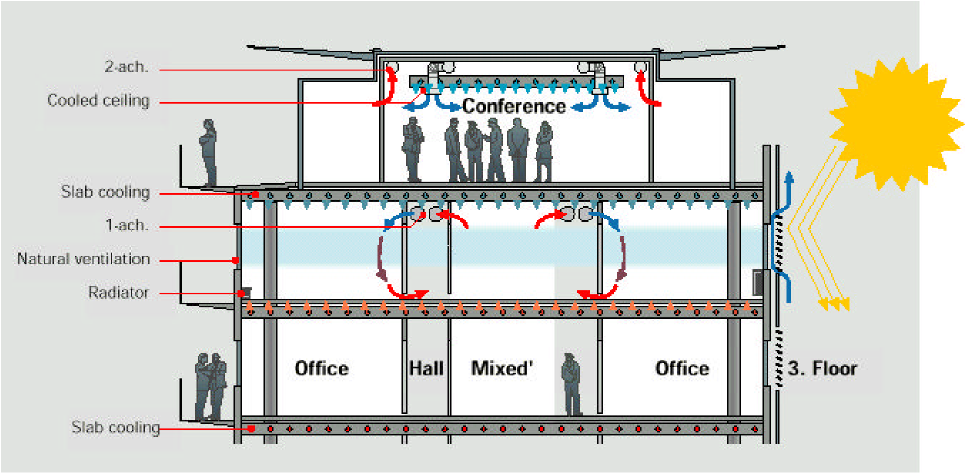

Figure 6: Office building in Munich with concrete slab heating/cooling, ventilation system, outside sunscreens and radiators.

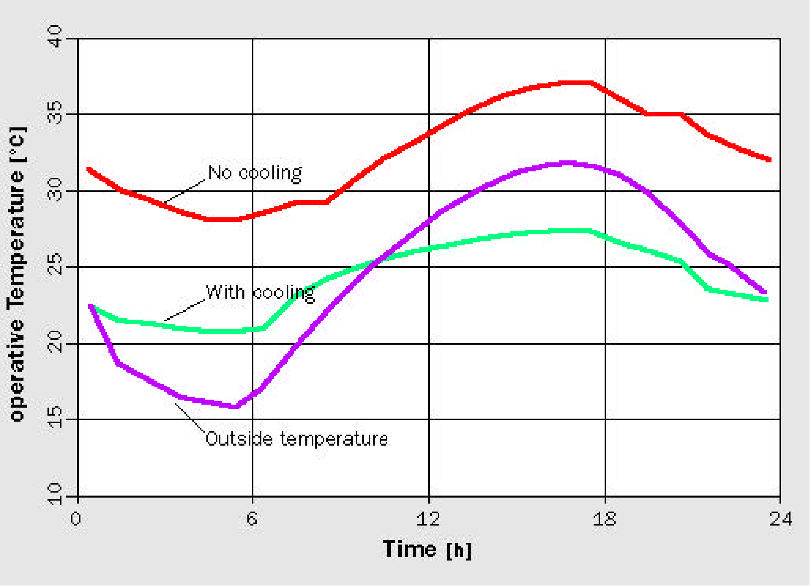

Figure 7: *Computer simulation for the office building in Munich.*

Museum in Bregenz

Due to protection of art other indoor requirements are needed for a museum than for an office. Especially the rate of temperature and humidity changes may cause damage to art. **Table 4** is listing some of the temperature and humidity specifications which were used for the design of a museum in Bregenz.

Table 4: *Data for the art museum in Bregenz*

Floors	4
Floor area	2.800 m²
In operation	1997
Concrete slab cooling in ceilings and walls	28.000 m of plastic pipes
Heating	Gas boiler
Cooling	Plastic pipes in concrete foundations and pillars
Design room temperature	Summer 22-26 °C Winter 18-22 °C
Design relative humidity	Summer 52-58 % Winter 48-54 %
Design people load	250 pr. day, 2 hours
Ventilation	750 m³/h pr. floor

The four storey building (**Figure 8)** has a double skin external envelope with an outer opened glass wall. In the original design an air conditioning system with 25.000 m³/h air was planned. Due to difficulties in getting space for the ducts and the visibility of the ducts between the glass ceiling and the concrete slab another solution was needed (Meierhans 1993, 1998).

The main goals was the continuity of the relative humidity, as well as the avoidance of both noise and dust. The solution, which also takes advantage of the cooling ability of the concrete core, is shown in **Figure 8**. The main objective of this project was not the phase shift of the cooling into the night hours. On the contrary, as the freely available cooling potential of the groundwater is always accessible and the phase shifting would cause temperature swings with too large amplitudes, therefore the cooling is applied over the entire day. The cooling medium is a water circuit embedded in 24 posts 18 m deep into the ground with large layers of groundwater.

All the exterior walls of the building are equipped with plastic pipes and exterior insulation to completely cut the connection with the exterior climate. The only connection is through the outdoor air supply. For this, a volume flow of 750 m³/h is used (**Figure 8**). The incoming air will be supplied to the building with a constant temperature and humidity through displacement ventilation slits

(**Figure 8**). During the year, the concrete core temperature can be controlled according to the seasons. However, during peak times such as exhibition openings, it is planned to switch the supply air set points to a lower level.

Assuming that the exterior climate is cut off completely, the concept basically differentiates between two heat sources (**see Figure 8**).

Dry heat sources, which only heat the air and consequently reduce the relative humidity (daylight and artificial light in the ceiling are (zone 2).

Dry and latent heat sources, which at the same time increase humidity(a variable number of people in the occupied zone 1).

Sensible heat, which is accumulated in the ceiling void through daylight and/or artificial light, will be removed directly to a large extent by radiant cooling and the exhaust air system. The combined load (sensible and latent) that is accumulated due to the presence of people in the room will be handled separately. While the required maximum temperature variation within 4 K pr. day (**Table 4**) can be obtained relative easy, the maximum variation of 6 % for the relative humidity (**Table 4**) is more difficult to fulfil. During a year the relative humidity may according to the specifications be 48 % in winter and increase up to 58 % in summer.

Important for the design of the heating/cooling system and the air system was an accepted room temperature of 18 °C in winter and that the temperature in summer during an art opening may increase up to 28 °C. The design for a normal day was based on 250 persons visiting for an average period of 2 hours distributed over the whole building. By an art opening it was assumed that 250 persons would occupy one room (floor) for the first hour and then distributed on all floors for the next two hours.

Significant for the control of the relative humidity was the split into two zones (Figure 7) and the low air change rate (750 m^3/h pr. floor). The dry heat from the sun and the artificial lightening was removed by the cooled slab and the exhaust air in zone 2. In this way it will not dry out the air in zone 1 where the art exhibition is. The low air change rate in zone 1 would in wintertime, with the dry outside air, only have a small effect on the relative humidity in the building. Also the fact that people do not only heat up a space by their dry heat loss, they also increase the absolute humidity by the latent heat loss will result in only minor variations of the relative humidity.

The first control concept is to control the water temperature at 22 °C, summer and winter. If the room temperature in winter drops below 22 °C the system heats and when in summer the room temperature increases above 22 °C the systems cools. In zone 1 the heat from people is removed by the pipes embedded in the walls and in the concrete slabs (floors).

The energy for cooling is supplied alone by the heat exchange between the pipes embedded in the foundation pillars/walls and the ground (**Figure 8**). The heating is provided by a gas boiler.

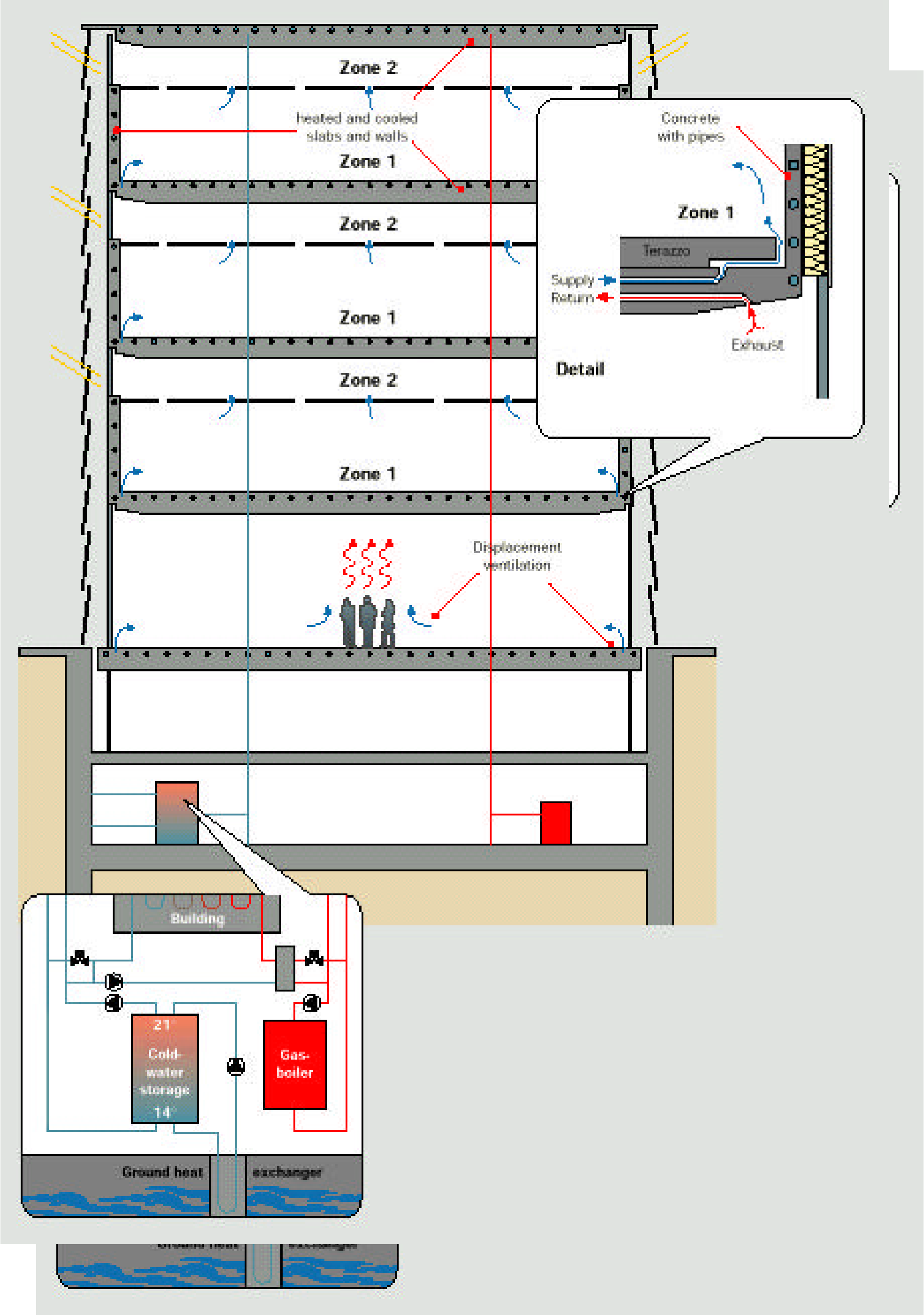

Figure 8: Museum in Bregenz with pipes embedded in walls and concrete slabs for heating and cooling. Details show the displacement ventilation and the generation system for cooling and heating.

Office building in Hamburg

The office building consists of two parallel office buildings and an office building constructed like an arch (**Figure 9**). Some of the main data for the building are listed in **Table 5**. The building has almost 100 % glass facades with external sun shading devices.

The main cooling and heating system is plastic pipes embedded in the 30 cm thick concrete slabs. Additional cooling is obtained by a mechanical ventilation system, 2 ach and 18 °C supply air temperature. For some rooms with higher internal loads like conference rooms, computer rooms etc. additional cooling equipment was installed.

***Table 5**: Office building in Hamburg*

Floors	11
Floor area, offices	14.000 m^2
Concrete slab cooling	7.500 m^2
Baseboard heaters	2 ach, 18 °C
Ventilation System	
Operable windows	

***Figure 9**: Office building in Hamburg*

The basic heating is provided by the concrete slab system and in addition baseboard heaters installed at the exterior surfaces.

Computer simulation and full scale test on a mock-up room was made to evaluate the performance (Müller, 1999). In the full scale test room a five days warm summer week and system combinations were tested.

A: Natural ventilation without cooling.

B: Natural ventilation with concrete slab cooling.
C: Mechanical ventilation with concrete slab cooling.

The room was exposed to cycling outside temperatures up to 31 °C each day during a 5 days week together with internal loads from computer, people, light and sun.

The measurements started at steady state conditions with all temperatures equal to 24 °C. The mechanical ventilation had a supply air temperature of 18 °C and the water temperature in the slab cooling system was 20 °C. **Table 6** shows the measured temperature ranges for the three conditions during 24 h, and during the time of occupancy for the 2nd and the 5th day. Without any cooling and only natural ventilation the room temperatures increase day by day. With cooling there is from the second day no change in the room temperature profile. The results from the test show that the slab cooling is decreasing the room temperatures with 5 to 6 K compared to no cooling and with mechanical ventilation (2 ach, 18 °C supply temperature) is decreasing the room temperature is decreased a further 1 to 4 K.

Table 6: *Results of temperature measurements in a laboratory test of a space with concrete slab cooling (Müller, 1999).*

Test	Room (Globe) Temperature Range			
	2nd day		5th day	
	24 h °C	Occupied time °C	24 h °C	Occupied time °C
A: Natural ventilation No cooling	25.5-31.1	26.0-31.1	28.8-33.2	29.3-33.2
B: Natural ventilation Concrete slab cooling	22.6-28.5	23.0-28.5	22.5-28.5	23.0-28.5
C: Mechanical ventilation Concrete slab cooling	22.0-25.1	22.0-25.0	21.8-25.0	22.0-24.8

CONTROL

When using surface systems for cooling it is important to control surface temperatures or water temperatures to avoid condensation. One possibility is to set a lower limit for the supply water temperature (Olesen, 1997a) to equal the dew point temperature, i.e. absolute humidity in the space.

In many applications surface heating and cooling systems are combined with a ventilation system. In this case the supply air is preconditioned to obtain a supply air temperature lower than the space temperature and remove latent loads by dehumidification. In this way the humidity, i.e. the dew point, will be controlled and the performance of the radiant cooling systems is then increased.

Using pipes embedded in the concrete slabs will result in a system with a very high thermal mass. In this case individual room control is not applicable. In most cases a zone control (south-north), where the supply water temperature , the average water temperature or the flow rate may differ from zone to zone, is used.

Relative 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 this temperature difference will influence the heat transfer between the cooled or heated surface and the space significantly.

For a well designed building with a low heating and low cooling load a concrete slab system may be controlled at a constant core (water) temperature year round. If for example the core is kept at 22 °C the system will heat at room temperatures below 22 °C and cool when the room temperature increases above 22 °C.

ENERGY SOURCE

Hydronic concrete slab cooling and heating systems can use relative high water temperatures for cooling and relative low water temperature for heating. This increases the possibility of using renewable energy sources like ground heat exchangers, solar energy for heating and cooling and free night cooling. It also increases the efficiency of boilers, refrigeration machines and heat pumps (Steimle, 1999). On top of that the slab system may use cheaper night rate electricity.

CONCLUSION

The possibility of using hydronic systems with pipes embedded in the building structure for heating and cooling of buildings has been discussed. The paper shows that for well designed buildings, these types of systems provide an interesting and viable alternative to full air-conditioning. As the heating and cooling capacities of such systems are limited, they require a careful design. These types of system can only add or remove sensible heat from a space. To remove the latent heat, the system need to be combined with a forced air system. This forced system can, however, be scaled down with the benefit of improved comfort (noise, draft) compared with full air-conditioning. An added benefit can be the reduced building height by omission of suspended ceilings. Finally surface heating and cooling systems use water at a temperature close to the room temperature. This increases the possibility of using renewable energy sources and increasing the efficiency of boilers, heat pumps and refrigeration machines.

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TABLES

Table 1: Total heat exchange coefficient (convection + radiation) between surface and space for heating and cooling, acceptable surface temperatures and capacity by 20 °C room temperature for heating and 26 °C room temperature for cooling (Olesen, 1997 b, Olesen et. al. 2000).

Table 2: Results of a computer simulation in "Degree Hours", where an operative temperature of 26 ^{o}C is exceeded. The calculations were made for different room types and orientations(Hauser et.al.2000) .

Table 3: Data for an office building in Munich

Table 4: Data for the art museum in Bregenz

Table 5: Office building in Hamburg

Table 6: Results of temperature measurements in a laboratory test of a space with concrete slab cooling (Müller, 1999).

FIGURES

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

Figure 2. Calculated air-, operative-, floor-, ceiling-, average slab- and slab core temperatures for a space with a constant internal load of 90 W/m^2 from persons, light, sun etc. Upper part without cooling, middle part with constant core (water) temperature of 20 ^{o}C and lower part with cooling only outside the time of occupancy (Meierhans and Olesen, 1999).

Figure 3. Central room module used for the computer simulation of a building with concrete slab cooling. All dimensions are in meter.

Figure 4: Cumulative number of hours where the operative temperature exceeds a certain value for no cooling, 24 h cooling (Strategy A) and 9 h cooling (Strategy B).

Figure 5: Office building in Munich

Figure 6: Office building in Munich with concrete slab heating/cooling, ventilation system, outside sunscreens and radiators.

Figure 7: Computer simulation for the office building in Munich.

Figure 8: Museum in Bregenz with pipes embedded in walls and concrete slabs for heating and cooling. Details show the displacement ventilation and the generation system for cooling and heating.

Figure 9: Office building in Hamburg.