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Radiant heating and cooling by embedded water-based systems

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INTRODUCTION

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. 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 (Simmonds et al. [1]; Olesen [2]). 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 [3]), 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 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.
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 [4]) show that floor heating control the room temperature as good 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. Design and dimensioning of these systems including calculation of heating and cooling capacity can be done according to the standards EN15377-1 and 2. [5, 6]

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 min. and max. 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 temperatures and cooling and heating capacity (EN15377-1).

		Total heat exchange coefficient W/m²K		Surface temperature °C		Capacity W/m²	
		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 15377), 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. This is also why floor cooling is increasingly used in spaces with large glass surfaces like airports (Simmonds et. al. [1]), atriums and entrance halls.

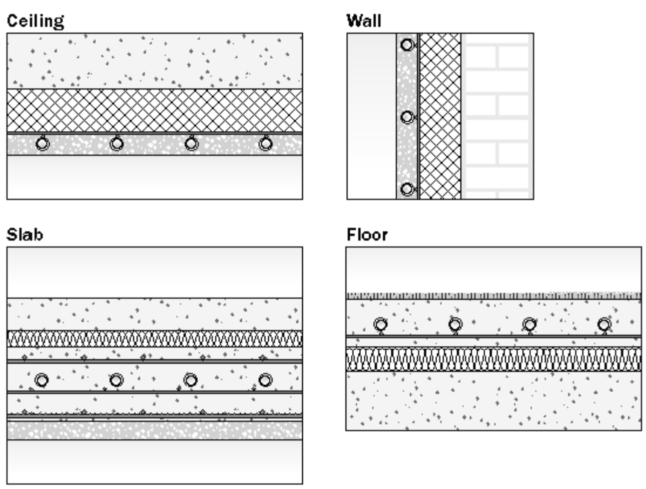

Figure 1. Examples of the positioning of pipes in floor, wall, ceiling and slab.

Thermo Active Building Systems (TABS)

A Thermo-Active-Building-System (TABS) is water based heating and cooling system, where the pipes are embedded in the central concrete core of a building construction.

The heat transfer takes place between the water (pipes) and the concrete, between the concrete core and the surfaces to the room (ceiling, floor) and between the surfaces and the room. The peak-shaving is the possibility to heat and cool the structures of the building during a period in which the occupants may be absent (during night time), reducing also the peak in the required power (Figure 2). In this way energy consumption may be reduced and lower night time electricity rate can be used. At the same time a reduction of the size of cooling system including chillers is possible.

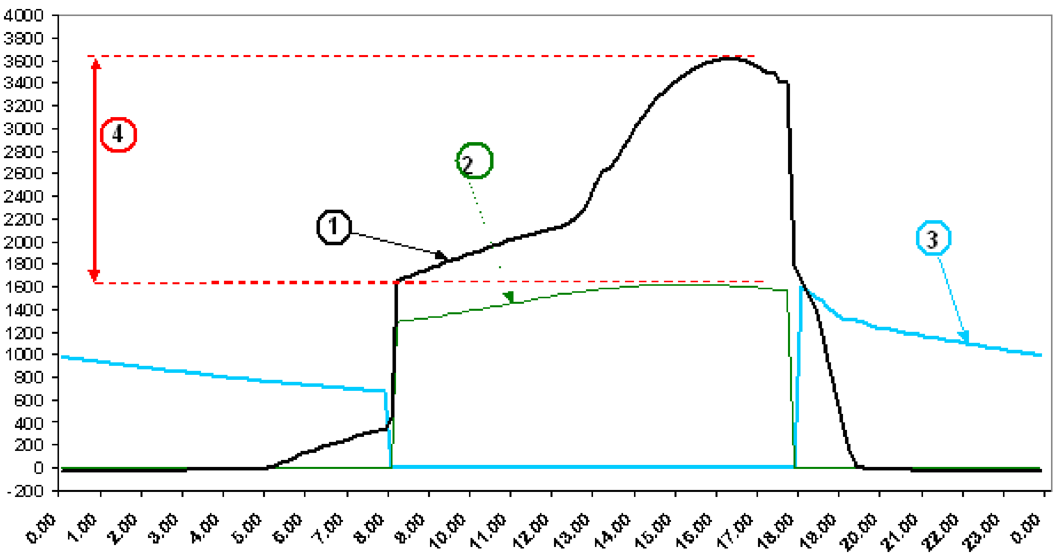

Figure 2– Example of peak-shaving effect (X-axes: time; y-axes: cooling power W)
1) heat gain, 2) power needed for conditioning the ventilation air, 3) power needed on the water side, 4) peak of the required power reduction

The performance and dimensioning of TABS can be done by full dynamic building simulations with commercial programs including calculation models for embedded pipes. (Olesen and Dossi, [7]). A study was performed with the aid of the dynamic simulation program. The system considered is a TABS system in a multi-storey office building. The meteorological ambient boundary conditions correspond to those of Würzburg/Germany and Venice/Italy. Summer was the period from 1 May to 30 September. 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: d*uring occupied periods corresponding to 27.8 W/m^{2}. *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.

The goal for the system used in the 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.
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:

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

Average water temperature 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:

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

The results of the simulation are shown in Table 2 for summer conditions. The operative temperature of the cases 0801 and 1401 (Table 2) 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. In the case of 1401, the control does not take into account the internal operative temperature, but the results are almost identical to cases 080. 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 and 1401 in Venice. For Würzburg, case 1401 has the lowest energy use, about 10% lower than case 801. Energy use in case 1201 with a constant water temperature is relatively high. The pump running time for case 1401 is equal to or lowers than for the other cases. In the summer, case 1401 is overall better than the others. Due to the warmer climate in Venice the room temperatures are higher, and energy use and pump running time are also higher compared to Würzburg. Standard EN15377-3 [8] includes more simplified methods to evaluate the dynamic performance of TABS.

EXERGY ANALYSIS

Energy carriers like fossil fuels deliver high valued energy. The reason for "energy saving" being in quotation marks in the first sentence, is that we actually are talking about saving exergy, not energy!
Future buildings should be planned to use or to be suited to use sustainable energy sources for heating and cooling. One characteristic of these energy sources is that only a relatively moderate temperature level can be reached, if reasonably efficient systems are desired. The development of low temperature heating and high temperature cooling systems is a necessary prerequisite for the usage of alternative energy sources. The basis for the needed energy supply is to provide occupants with a comfortable, clean and healthy environment.
Figure 7 is showing an example of a calculated energy flow and exergy flow from primary energy, heat generator, emission in room and loss to the outside. The figures show that a low temperature heating system will result in less exergy consumption.

Table 2: 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 = 22°C 1201	Supply=F (outside) 1401	Supply=F (outside) 0801	Average = 22°C 1201	Supply=F (outside) 1401
Operative temperature interval	°C	%	%	%	%	%	%
	<20	0	0	0	0	0	0
	20-22	0	0	0	3	1	5
	22-25	56	8	56	75	30	77
	25-26	26	13	25	18	21	14
	26-27	13	19	14	5	22	4
	>27	5	60	5	0	27	0
Pump running	hours	1254	1417	1214	1091	1327	953
	% of time	34	39	33	30	36	26
Energy KWh	Cooling	1104	1297	1106	763	978	749
	Heating	1	0	0	29	2	2

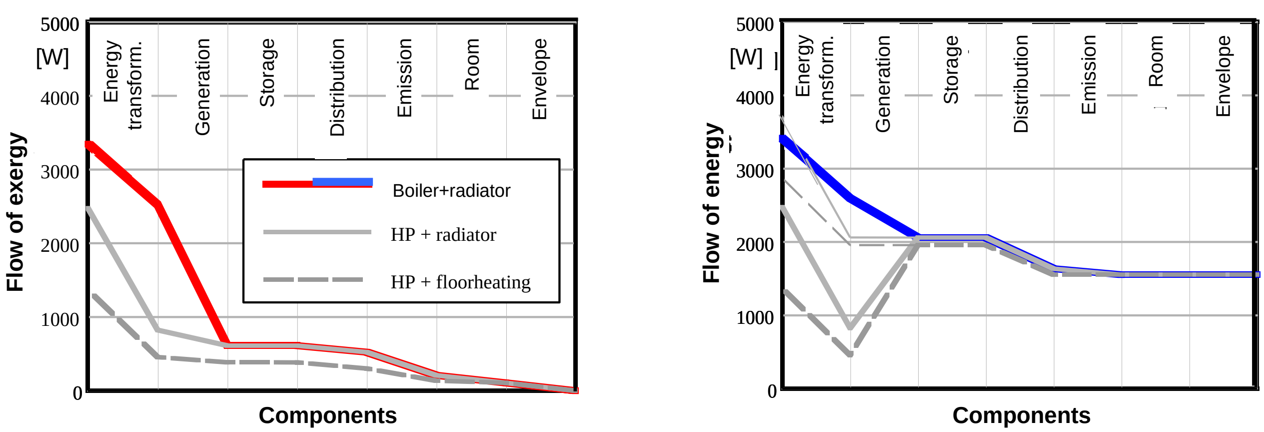

Figure 3 Examples of exergy and energy flow for three type of heating systems. (IEA-Annex 37)

DISCUSSION AND CONCLUSIONS

New demands for lowering the energy consumption of buildings require increased insulation of houses, tight constructions with mechanical ventilation and heat recovery. A trend for residential building is the concept of passive houses, where a “normal” heating system may not be needed. This trend will result in much smaller heating systems and in many cases systems using air as the energy transport medium. Also the global warming will result in less need for heating.

Another trend in Europe is the increasing need for cooling. Peoples increased comfort requirements (air conditioning in cars), increasing thermal loads in many office buildings, global warming, heat islands and the aim for optimal productivity of people, are all issues that will result in a higher demand for cooling.
In middle Europe a trend to use water based cooling systems at high water temperature is a way of making the cooling more sustainable with less energy consumption compared to full Air Conditioning. Some of these systems also use the building mass (TABS) to reduce the peak cooling load and transfer some of the cooling from daytime to night-time.
This trend has resulted in new CEN standards for design and dimensioning of systems and evaluation of the dynamic effect. Also new research studies are looking at the performance and optimal control of such systems.
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 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 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.

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