Applications of radiant floor cooling systems

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ABSTRACT

The use of floor heating has been know since more than 3000 years from the Chinese Kang, the Korean Ondol, the Romans hypocaust to days modern water based systems embedded in the floor construction. The application of such systems also for cooling is however less known. To evaluate the usefulness of radiant floor cooling it is important to take into account comfort, cooling capacity, control and design. One limiting factor is the floor surface temperature. In spaces with seated or people the floor temperature should not be lower than 20 °C for comfort reasons. For higher activity levels a lower floor surface temperature may be acceptable and the limitation will then be the dew point temperature in the space. The heat exchange coefficient between a cooled floor and the room is typically around 7 W/m² °C where 5.5 W/m² °C is radiant heat transfer. In spaces with mainly seated occupants the upper comfort limit for the operative temperature in summer is 26 °C. This means that based on the heat exchange between the floor surface and the room a maximum cooling capacity for a floor system is 40-50 W/m². In several spaces like atrium, entrance hall or other spaces with window facades there will often be a lot of direct sunshine on the floor. In these cases the cooling capacity is significant higher and may reach 100-150 W/m². The influence of these parameters is discussed in the paper and several applications are presented.

1 INTRODUCTION

In many countries hydronic radiant floor systems are widely used for heating of all type of buildings like residential, churches, gymnasiums, hospitals, hangars, storage buildings, industrial buildings and smaller offices, but very few systems are also used for cooling purposes.

Reasons like free use of space, uniform temperature distribution and a low temperature heating system have made many people choose floor heating. 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 in the introduction in the use of floor systems for cooling (Borresen 1994, Olesen 1997, Simmonds et al. 2000).

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.

More than half the thermal energy emitted from a floor heating system is in the form of radiant heat. The radiant heat exchange influences directly the heat exchange with the occupants and surrounding surfaces like walls and ceiling. In this way a uniform thermal environment is established. Due to the high radiant heat output and that the occupants are close to the floor surface makes it obvious to try to use the same floor system also for cooling. The convective heat exchange coefficient for floor cooling is, however much lower as for floor heating. There are also several comfort factors like acceptable floor temperature, vertical air temperature difference, radiant asymmetry and dew point temperature which may reduce the cooling capacity of a floor system. Besides the floor construction (slab thickness, floor covering,) and system (type of pipes, distance between pipes, water flow rate) may limit the cooling capacity. Therefore the design of a floor system for highest cooling capacity may be different than for heating.

The present paper describes the concept of a floor cooling system including thermal comfort of the occupants, which design parameters will influence the cooling capacity and how the system should be controlled. Finally some examples of applications will be presented.

2 THERMAL COMFORT AND FLOOR COOLING

The purpose of heating and cooling of occupied buildings is to provide an acceptable thermal environment for the occupants. The thermal environment may be described by the following parameters: Thermal insulation of the occupants clothing, activity level of the occupants, air temperature, mean radiant temperature, air velocity, and humidity (ASHRAE 55 2004, ISO EN 7730 2005). The combined influence can be described by the PMV-PPD index (ASHRAE 55 2004, ISO EN 7730 2005). To provide thermal comfort it is also necessary to take into account local thermal discomfort, which may be caused by radiant temperature asymmetry, draught, vertical air temperature differences and too warm or too cool floor temperatures.

2.1. Operative temperature

The two main parameters for providing acceptable thermal conditions in a space and which may be significantly influenced by the heating/cooling system are the air temperature and the mean radiant temperature. The combined influence of these two temperatures is expressed as the operative temperature. For low air velocities (<0.2 m/s) the operative temperature can be approximated with the simple average of air and mean radiant temperature. This means that the air temperature and the mean radiant temperature are equally important for the level of thermal comfort in a space. For radiant cooling system an important factor is the angle factor between the occupants and the radiant heat source or sink (Michel and Isoardi 1993). This factor depends on the distance between a person and the surface and the area of the surface. This means a floor normally has the highest angle factor of all surfaces (walls, ceiling, windows etc.) in a space to the occupants. For a person positioned at the center of a 6 by 6 m floor the angle factor is 0.40 for sedentary. For a 12 by 12 m floor the corresponding angle factors are 0.46. This should be put in relation to the angle factor for a half room, 0.5. If the floor surface temperature is decreased by 5 °C and all other surface temperatures are assumed to be unchanged, then the mean radiant temperature will decrease by 2 °C. The impact on an occupant is expressed by the operative temperature, which will decrease by 1 °C. Put in another way a 5 °C lower floor surface temperature will have the same cooling effect as lowering the air temperature by 2 °C.

In most standards (ASHRAE 55 2004, ISO EN 7730 2005) the upper limit for the operative temperature in summer is 26 °C for spaces with mainly sedentary occupants (1.2 met) and a summer clothing (0.5 clo).

2.2. Floor surface temperature

As mentioned above discomfort may occur at too low or too high floor temperatures. In most national and international standards (ASHRAE 55 2004, ISO EN 7730 2005) a floor temperature interval of 18/19 to 29 °C is recommended for rooms occupied with sedentary or/and standing people wearing normal shoes. For sedentary persons a lower limit of 20 °C for floor cooling is normally used.

2.3. Vertical air temperature difference

It is normally recommended to limit the air temperature difference between ankles (0.1 m level) and head (1.1m level) to 3 K for sedentary persons (ASHRAE 55 2004, ISO EN 7730 2005) Because most of the heat exchange between a cooled floor and the space is by radiation, the air at the ankle level will not be cooled very much due to the low convective heat exchange. The vertical air temperature differences with floor cooling will then not cause any discomfort. This has been confirmed in an experimental study (Michel and Isoardi 1993). In this study the vertical temperature differences are less than 0.5 K which is similar to the vertical temperature difference 0.4 K without floor cooling. Another experimental study (Deli 1995) shows somewhat higher values (Fig. 1) but still within acceptable comfort limits.

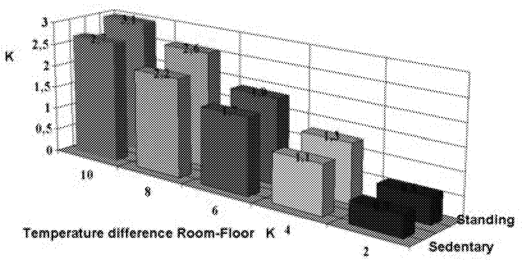

Figure 1. Vertical air temperature difference floor cooling.

2.4. Humidity

A limiting factor for the floor temperature and then the cooling capacity is the dew point temperature in the space. Some standards (ISO EN 7730 2005) recommend a limit for the relative humidity in a space to 60 or 70 % rh, which corresponds at an air temperature of 26 °C to a dew point between 17 and 20 °C. Others (ASHRAE 55 2004) recommend an absolute humidity level of approx. 11.5 g(H_20)/kg, which corresponds to a dew point of temperature 16 °C.

This means the floor surface temperature must be higher than 16 to 20 °C. The use of dehumidification in a room by an air conditioning system or a simple dehumidifier will decrease the dew point temperature and then increase the cooling capacity of a floor system.

3 COOLING CAPACITY OF A HYDRONIC FLOOR SYSTEM

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.

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/m^2K, the convective heat exchange coefficient will change. The listed 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/m^2 (Borresen 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. This has been included in a new European standard (EN 15377-1 2007) for calculation of the heating and cooling capacity of floor, wall and ceiling systems. The heat exchange for floor cooling is based on an experimental study (Olesen et al. 2000). Figure 2 (REHVA 2007) shows a diagram based on this standard, where the cooling capacity and heating capacity for a typical floor system is shown.

4 DESIGN

A floor heating system is often designed with a tube spacing of 150 mm or higher. To increase the cooling capacity it may, however be necessary to design a floor cooling system with a smaller spacing. A water flow rate in a floor

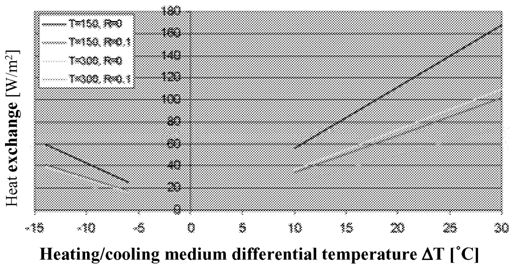

Figure 2. Floor heating and cooling (type A), R=0.01~0.1, T=150~300.

heating system is often based on a water temperature difference of 10 °C between supply and return. Again to increase the cooling capacity and avoid too low supply temperatures (condensation risk) a floor cooling system should be design with a 3 to 5 °C temperature difference between supply and return water. This means a higher water flow rate and then a higher pressure drop in the tubes. This may then be necessary with a larger pump or the use of smaller tube circuit but still obtain enough flow rate to establish a turbulent flow. For maximum cooling capacity it is important to avoid floor coverings with a high thermal resistance like heavy wall to wall carpets.

5 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 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.

A control diagram for a combined floor heating-cooling system is shown in figure 3. For heating the average value of the supply- and return water temperature is controlled according to the outside temperature (flux control). In addition an individual room control may control the water flow rate to each room individually. For floor cooling the supply water temperature is also controlled according to the outside temperature with a limiter based on the dew point temperature in a reference room. In addition an individual room control may be set to shut-off or open for the water flow to each room individually.

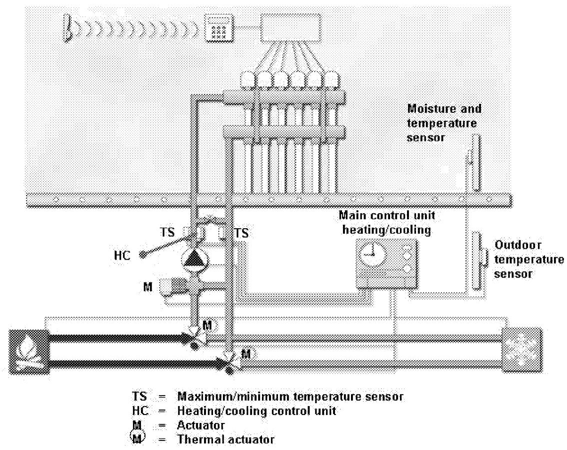

Figure 3. Floor heating-cooling control.

6 COOLING SOURCE

As a floor system is a high temperature cooling system and a low temperature heating system it will provide a high efficiency of a heat pump. This can be an air/water, water/water, ground/ water type or an absorption heat pump. As the ground temperature often is around 10 °C it will also be possible directly from a ground heat exchanger to cool a floor without the use of a heat pump.

A floor cooling system may often be used together a convective cooling system. Then the floor system may take most of the sensible load, while the air system will take care of the latent load. At the same time the dew point in the space will be lowered and a higher cooling capacity of the floor system may be obtained. Another advantage is the high return water temperature form a floor system, 18-20 °C, which will increase the efficiency of a refrigeration machine.

7 APPLICATIONS

Floor cooling can basically be applied everywhere were also floor heating can be applied (one family houses, multi-family houses, offices, industrial buildings (hangars, storage spaces, large halls etc.), museums, sports facilities, churches etc. The system types are also the same. Floor cooling is particular efficient in large spaces with large windows, where you can expect a significant influence of sun radiation either directly or due to a very warm ceiling or wall surface (Atria, airports, shopping malls etc). The floor cooling will absorb the sun radiation before it heats up the space.

Floor cooling in Southern Europe

The objective of the study was to evaluate the potential for floor cooling in Italy, Spain and Portugal. The evaluation is based on a dynamic computer simulation of a room in a house or apartment using the commercially available program IDA-ICE. The program is using Test Reference Year weather date for different locations in Spain, Portugal and Italy (Figure 4). The type of room in a multistory apartment or a single family house was typical for the country studied. The operative temperature during the cooling (summer) period from April to October was for evaluation of the cooling performance of a floor system. In Palermo the operative temperature is higher than 26 C more than 30% of the time and in Rome above 26 C for 10 % of the time; but never above 28C in Rome. For all other locations the room operative temperature only exceeds the 26 C less than 5 % of the time.
One of the main criteria is to avoid condensation of water on the floor and in the system.
Therefore all of the simulations have a required minimum water supply temperature higher than the dew-(absolute humidity) in the room. Therefore the simulation program is also making a humidity balance for the room taking into account outside humidity and internal production of humidity from the people. The results in figure 5 show the importance of dehumidification in certain locations as Palermo and Rome. While in Braganca there is no need for dehumidification.

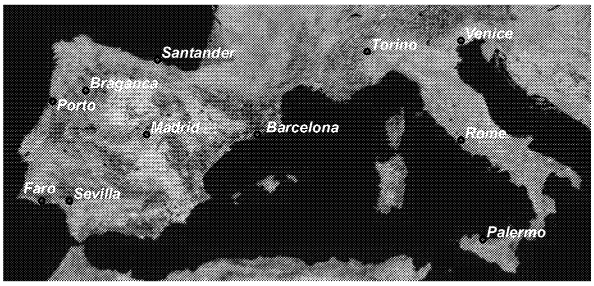

Fig. 4. Locations for studying the application of radiant floor cooling in residential buildings.

The results indicate that in Italy it is recommended to use dehumidification in regions south of Firenze. Further north it will be acceptable without. If however a wooden floor and dry-system type is used, with higher internal loads it may be a need for additional dehumidification a part of the year.

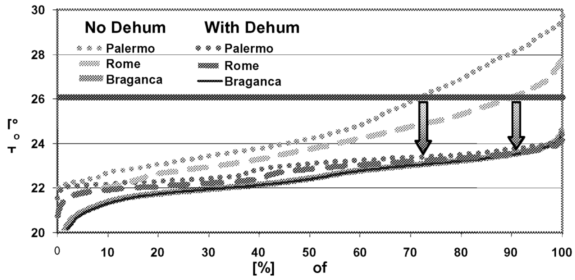

Figure 5. Distribution of room operative temperatures for three geographical locations. Results both with and without dehumidification.

One of the great benefits of this system is the combined use for heating and for cooling. Therefore in regions where heating is needed there are many good arguments for using a floor system with combined cooling in summer. Is there only need for cooling, it may be more difficult to argue for a floor system
The new Bangkok International Airport

The world largest construction with floor cooling is the new airport in Bangkok (Simmonds et al. 2000). Here 150.000 m^2 of floor heating is installed in the concourses and main terminal buildings. The roof over the concourses (Figs 6) consist of glass and a plastic membrane construction. Due to the high outside temperatures and sun radiation this will result in a very high cooling load. A combination of displacement ventilation and floor cooling has been installed (Fig.6). The floor cooling was dimensioned to remove 70-80 W/m^2 with a supply water temperature of 13 °C, return water 19 °C and a floor surface temperature of 21 °C. The manifolds for the floor system were installed inside the displacement air diffusers. As the dew point in the supply air is 10-12 °C and lower that the supply water temperature, there will be no risk for condensation on the pipes. The design dew point in the space was 16 °C due to evaporation from the occupants. This is still 5 °C lower than the surface temperature of the chilled floor. Compared to a full air system a 30% reduction of energy consumption was predicted during the design (Simmonds et al. 2000).

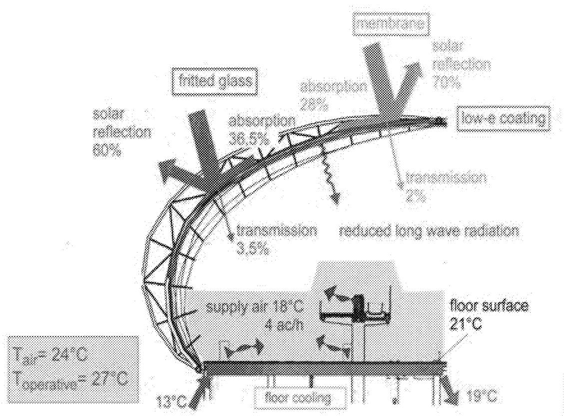

Figure 7. Optimized energy concept concourses.

8 CONCLUSIONS

- A hydronic floor cooling system provides sensible cooling with no discomfort due to noise, draft, obstacles and requirement for cleaning.

- The maximum cooling capacity is for most spaces less than 50W/m^2. In spaces with direct sunshine on the floor (Atrium, entrance hall, show room) the cooling capacity will be significantly higher and up to 100 W/m^2.

- A floor cooling system must be controlled to avoid condensation. This may be done by a supply water temperature controlled by the dew point temperature.

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