Evaluation of Performances, Thermal Comfort and Energy Consumption of a Reversible Radiant Ceiling by Capillary Mat: Application for the Prefabricated Buildings

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ABSTRACT

The objective of this paper is to analyse if Radiant Cooling Ceiling (RCC) has the potential to provide better comfort and energy consumption in prefabricated buildings by comparison with conventional systems installed on this structures. Another purpose of this paper is to investigate the risk of condensation on the ceiling panel and finding the solution to prevent this. A building energy simulation code called Trnsys was used to simulate the system and to analyse different characteristics of the RCC and of the indoor space. The results showed that during the summer period when in prefabricated buildings air temperatures could reach 35°C the RCC can assure almost the same thermal comfort like AC (air-conditioning systems) but with energy savings that have reached 21.5% in our studied case. Another important characteristic of radiant ceiling is its reversibility because it can be used also during the winter season to ensure the proper indoor conditions for the occupants. The figures and tables presented show that radiant ceiling can be integrated on these light structures offering well indoor conditions in terms of indoor temperature, humidity and without any risk of condensation during the summer period. We have found that the energy savings could reach more than 30% in hot and dry climates and 20% in moderate climate using the RCC.

KEYWORDS

Prefabricated buildings, radiant cooling, thermal comfort, condensation risk

INTRODUCTION

In the past years, Western European buildings are more often equipped with radiant systems insuring good thermal comfort (Miriel et al., 2002) even for relative high internal loads during the summer. Temporary dismountable constructions used on the building sites poses the problem of a big consumption of total energy and lack of comfort during the summer period if they are not air-conditioned, so another solution to cool them has to be found. An attractive solution is radiant ceiling systems that rely on chilled water pipes to distribute cooling throughout a building rather than a conventional system that uses chilled air. Radiant cooling systems rely mainly on the direct cooling of occupants by radiative heat transfer because the pipes, in our case the capillary mat, maintains the ceiling surface at temperatures between 17°C to 21°C depending on the risk of condensation. The capillary tube system consists of a mat of small, closely spaced tubes made in polypropylene that are embedded in gypsum, or plaster on walls and ceilings assuring almost perfect temperature homogeneity on the interior surfaces of the room.

SIMULATIONS HYPOTHESES

In order to simulate a radiant ceiling installed in a prefabricated building we have used the well known simulation program Trnsys (TRNSYS, 1994). Real technical data of this kind of building were introduced in the simulation program. The room dimensions are 6.055 m long, 2.435 m wide and 2.591 m height. The building structure is light with low inertia and with all the walls on the exterior. In Table 1 are presented the characteristics of the simulated building.

TABLE 1
Building materials thermal characteristics

Exterior walls and floor	Thickness [m]	Conductivity [W/mK]	Capacity [kJ/kgK]	Density [kg/m^3]	Uvalue [W/m^{2}K]
Plasterboard	0.01	0.157	0.84	950	0.562
Mineral wool	0.06	0.038	0.9	80	
Metallic protection	0.063	54	1.8	7800	
Ceiling	Thickness [m]	Conductivity [kJ/mK]	Capacity [kJ/kgK]	Density [kg/m^3]	Uvalue [W/m^{2}K]
Plasterboard	0.01	0.157	0.84	950	0.356
Capillary mat	0.003	0.21	1.17	1100	
Mineral wool	0.1	0.038	0.9	80	
Metallic protection	0.063	54	1.8	7800	

Two double-pane windows with a glazed area of 1.17m^2 and a U-value of 2.4 W/m^{2}K are installed on the North side of the building. We have considered that the entire surface of the ceiling is covered by capillary mat by means of three panels disposed in parallel for better temperature homogeneity. An occupancy pattern of one person with a schedule from 8 to 12 and 14 to 18 and two persons from 12 to 14 is simulated in the room. When present each person generates 75W sensible heat and 95W latent heat. Constant loads of 290W of equipment and lighting with a schedule from 8 to 18 are modelled in the room. An infiltration of 0.2 ACH and a ventilation rate of 2 ACH with outside air are also modelled. Concerning the parameters influencing the PMV calculations we have done the next hypotheses (see Table 2):

TABLE 2
Thermal comfort hypotheses

	Clothing factor [clo]	Metabolic rate [met]	External work [met]	Relative air velocity [m/s]
Winter case	0.5	1.2	0	0.2
Summer case	1	1.2	0	0.2

The set point in the room is 26.3°C of air temperature in summer for the radiant ceiling and 24.5°C for the AC system. These values have been adjusted in order to obtain a good and quasi equal comfort with the two systems. The piece key of the radiant ceiling simulated is the capillary mat made in polypropylene with an exterior diameter of 3 mm and with a thickness of 0.5 mm. The small distance of 1 cm between the capillary tubes makes this kind of radiant ceiling one the best in matter of temperature homogeneity on the surface of the ceiling or in other cases on the walls. For the summer case we have developed a control method to avoid permanently the risk of condensation. In Figure 1 is presented the control system adopted for the simulations. By analysing each hour the dew point temperature and comparing it with the ceiling surface temperature the condensation didn't appeared for the whole simulation.

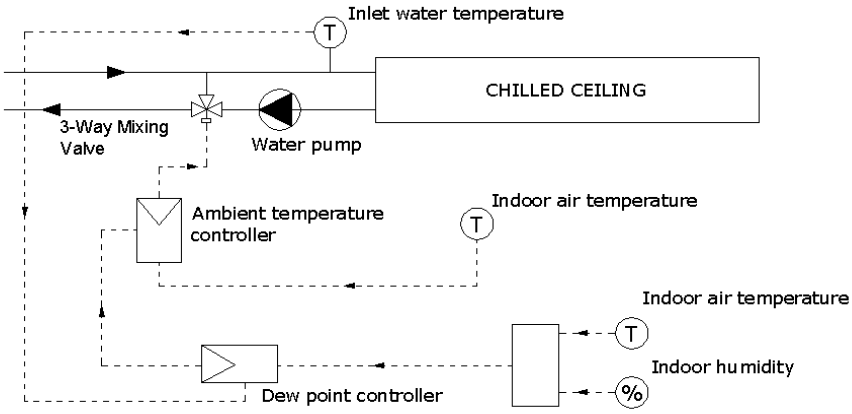

Figure 1: Control system used to avoid condensation on the ceiling

The water control is carried out locally in all the prefabricated buildings if there is more than one. The dew point temperature is calculated for each room by monitoring on each moment the ambient air temperature and the relative humidity. The inlet water temperature is controlled individually with values higher than the dew point of the ambient air.

SIMULATIONS RESULTS

The weather data used for the simulations corresponds to Lyon city. The climate for this region is moderate with maximum outdoor temperatures in summer around 32°C and in winter -8°C. In Figure 2 are shown the indoor air temperature and the mean radiant temperature compared to an AC system. Even the indoor temperatures passes 28°C few times because of the control system, the global PMV (Predicted mean Vote) of the building using the cooling ceiling is comparable to AC system. These temperatures may be acceptable knowing we do energy savings.

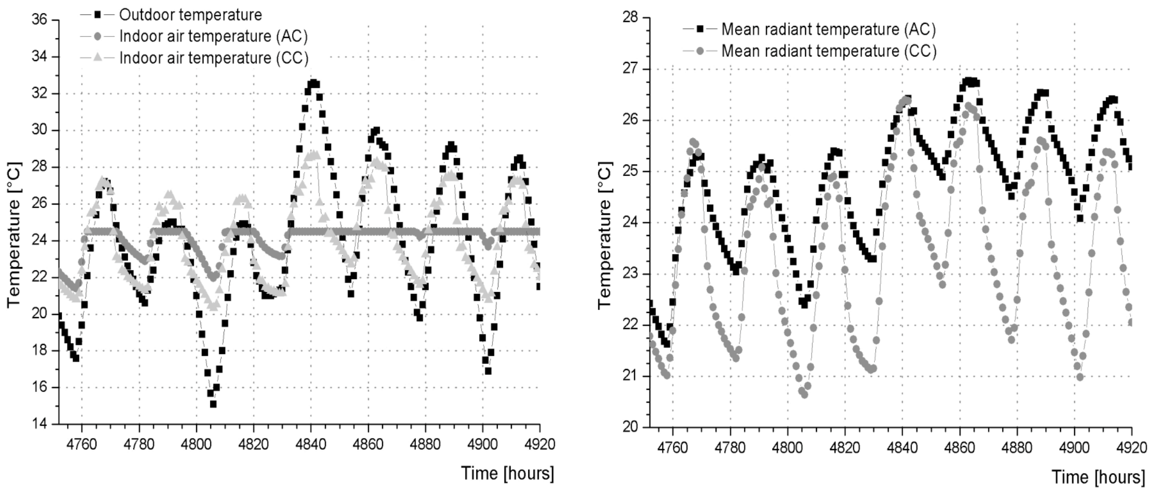

Figure 2: Indoor temperature and mean radiant temperature during the hottest week of the year

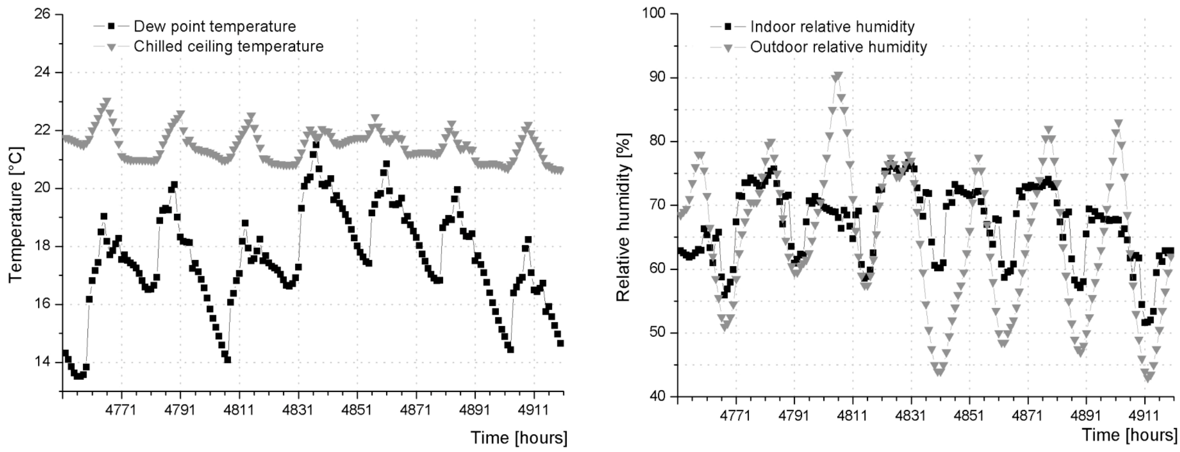

Figure 3: Indoor dew point temperature and humidity with the control system during the hottest week of the year

It is observed in Figure 3 that the control system is effective because the chilled ceiling surface temperature is maintained below the dew point temperature of the room avoiding in this way all risk of condensation. In Figure 4 are presented the water flows in the pipes obtained by the control system in order to avoid the condensation on the ceiling. It is noticed that for example at 13:00 pm where the indoor humidity is increasing because of the second person who comes in the room, the flow 1 with water at 17°C it's reduced to almost 0% of the total flow. These results clearly indicate that the condensation risk is higher when latent charges are increasing which it's normal but they indicate also that the control system seems able to prevent condensation.

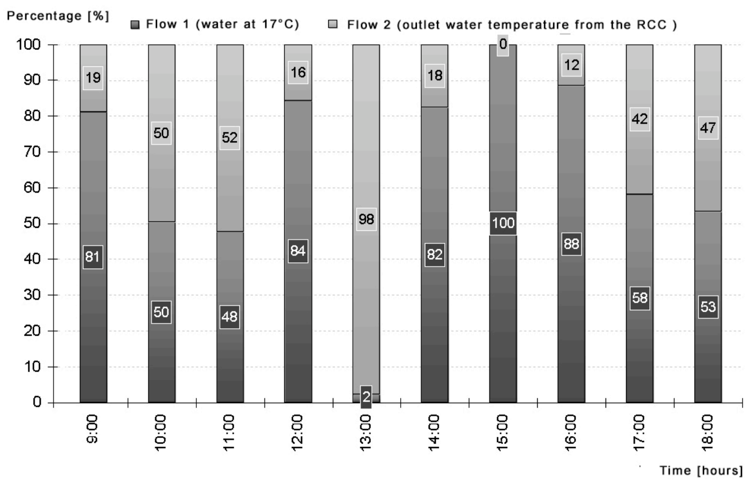

Figure 4: Water flows used to avoid condensation during one day

Concerning the specific cooling rate of the panels it was noticed that the maximum value for the summer case was 78 W/m^2. A calculation of PMV (ISO 7730, 1994) was done comparing the chilled ceiling and a classical air-conditioning system. The PMV passes during the entire summer the value of +0.5 only 16 times and with a maximum of +0.8, knowing that the simulation time step was 1 hour. The data obtained makes it possible to conclude that the cooling ceiling is an attractive solution even in some cases the indoor temperatures are higher than an air-conditioning system but with the big advantage of energy savings and without any air drafts.

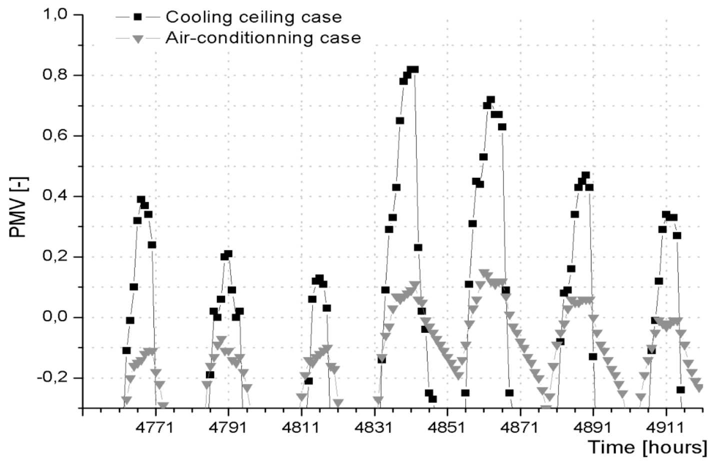

Figure 5: PMV coefficient for the air-conditioning compared to the cooling ceiling during the hottest week of the year

The simulations had allowed us to compare also the energy demand which in the case of AC system is 164.35 kWh during the summer period, more specific during the months of June, July and August. Using the cooling ceiling for the same period the energy demand is 128.98 kWh which represents an energy savings of 21.5%. The radiant system analysed reduces the environmental impact not only with the energy savings but also with the polypropylene used for the capillary mats who does not present any health disadvantages and it can be completely recycled.

CONCLUSIONS

Ceiling radiant cooling systems can be more comfortable than conventional air cooling systems, due to less air movement and offering calmer room environments. In addition, the room air temperature can be set higher than with convective air conditioning systems due to direct radiative heat exchange between the ceiling and the human body. Therefore, this system can reduce the cooling loads and contribute to energy saving. In our studied case the cooling load was reduced with 21.5% in comparison with the AC systems. However the advantages, in hot and humid regions, fears for the risk of condensation on ceiling panels limit its market penetration but with a good control system the risk of condensation is completely avoided. We have found that the control system adopted for our simulations seems capable to face hot and humid climates preventing the condensation on the ceiling. The results which we have obtained after the simulations shows that the radiant ceiling can be used on prefabricated buildings assuring almost the same thermal comfort like an AC system but with the advantages of energy savings, noise reduction and eliminating completely the air drafts.

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