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Evaluation of thermal comfort using combined CFD and experimentation study in a test room equipped with a cooling ceiling

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ABSTRACT

This paper reports a full-scale experimental campaign and a computational fluid dynamics (CFD) study of a radiant cooling ceiling installed in a test room, under controlled conditions. This research aims to use the results obtained from the two studies to analyze the indoor thermal comfort using the predicted mean vote (PMV). During the whole experimental tests the indoor humidity was kept at a level where the condensation risk was minimized and no condensation was detected on the chilled surface of the ceiling. Detailed experimental measurements on the air temperature distribution, surface temperature and globe temperature were realized for different cases where the cooling ceiling temperature varied from 16.9 to 18.9 °C. The boundary conditions necessary for the CFD study were obtained from the experimental data measurements. The results of the simulations were first validated with the data from the experiments and then the air velocity fields were investigated. It was found that in the ankle/feet zone the air velocity could pass 0.2 m/s but for the rest of the zones it took values less than 0.1 m/s. The obtained experimental results for different chilled ceiling temperatures showed that with a cooling ceiling the vertical temperature gradient is less than 1 °C/m, which corresponds to the standard recommendations. A comparison between globe temperature and the indoor air temperature showed a maximum difference of 0.8 °C being noticed. This paper also presents the radiosity method that was used to calculate the mean radiant temperature for different positions along different axes. The method was based on the calculation of the view factors and on the surface temperatures obtained from the experiments. PMV plots showed that the thermal comfort is achieved and is uniformly distributed within the test room.

1. Introduction

The majority of air-conditioning devices function using the principle of pulsated air, where the hot air of the room is partly recycled, cooled and returned into the room. The increase of the thermal loads in the buildings, mainly due to the arrival of office computers and lighting requirements, causes the installation of air-conditioning systems necessary to neutralize these loads and to create a good indoor thermal comfort. Heating, ventilating and air-conditioning (HVAC) systems, which consume large quantities of energy, have become a necessity for almost all the buildings [1] to provide a comfortable indoor environment.

Currently, the evacuation of these quantities of latent and sensible heats is done mainly with air treated, introduced by air diffusers. To maintain comfort under these conditions, a greater volume of cooled air must be provided to the working area. Many complaints about air-conditioning systems have been claimed, especially in summer by female occupants [2]. Disadvantages such as noise, cold-drafts, vertical air temperature gradient demand the research of other cooling systems which can create better indoor conditions and in the same time to be energy efficiently.

The use of water to cool the surfaces of the buildings is consequently a tempting alternative solution. It is even more appealing as water cooling requires much lower flow rates and higher temperatures of the water, so an energy consumption reduction could be achieved [3,4]. The chilled ceiling radiant panels are room cooling systems for placement in the ceiling zone, their cooling surfaces being connected with closed circuit heat conducting pipework containing flowing chilled water.

The main difference between cooling ceilings and air-conditioning systems is the mechanism of heat transfer. Classic air-conditioning systems are based only on the convection, while cooled ceilings employ a combination of radiation and convection.

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Nomenclature

d	distance to the wall [m]
F_{0j}	diffuse view factor
f_μ, f_2	damping functions
g	acceleration due to gravity [m s^{-2}]
k	turbulent kinetic energy [m^2 s^{-2}]
I_{cl}	clothing insulation [clo]
Pr	Prandtl number
Re	Reynolds number
M	metabolism [met]
MRT	mean radiant temperature [°C]
PMV	predicted mean vote
PPD	predicted percentage of dissatisfied [%]
T	mean temperature [°C]
T_{sj}	surface temperature [°C]
U	mean velocity magnitude [m s^{-1}]
u_i'	velocity fluctuation component [m s^{-1}]
x,y,z	coordinate [m]

Greek letters

β	coefficient of thermal expansion [K^{-1}]
μ	dynamic viscosity [Pas]
ν	kinematic viscosity [m^2 s^{-1}]
ε	dissipation rate of k [m^2 s^{-3}]
ρ	mass density [kg m^{-3}]
τ	turbulent time scale [s]

With cold ceilings, the transfer of radiant heat occurs by a clear emission of electromagnetic waves from the hot occupants and their environments to the radiant ceiling. The hot air arriving in contact with the cooled surface is cooled below the average temperature of the room and therefore falls down the zone of occupation [5]. With a cooling ceiling the temperature of water or its flow rate can be modified so that the surface temperature adapt to the desired conditions.

Ceiling radiant cooling systems can be more comfortable than conventional air cooling systems due to small vertical temperature gradient, few air movements and reduced local discomfort for occupants during long stays in cooled room environments. Catalina and Virgone [6] found after a series of simulations that the cooling ceilings offer good thermal comfort, the mean radiant temperature being an important parameter in the comfort evaluation.

Nagano and Mochida [7] analyzed the thermal comfort of five subjects in an experimental test room equipped with cooling ceilings. Their study aim was to clarify the control conditions of ceiling radiant cooling systems for human subjects in a supine position. They concluded that the mean radiant temperature for a supine human body should be used in the design of ceiling radiant cooling. It was also found that some of the subjects voted the strong radiant sensation even though the temperature difference between the ceiling and the room air was less than 5 °C in these experiments.

Kulpmann [8] reported an investigation of the thermal comfort in a test room equipped with a cooled ceiling surface and supplied

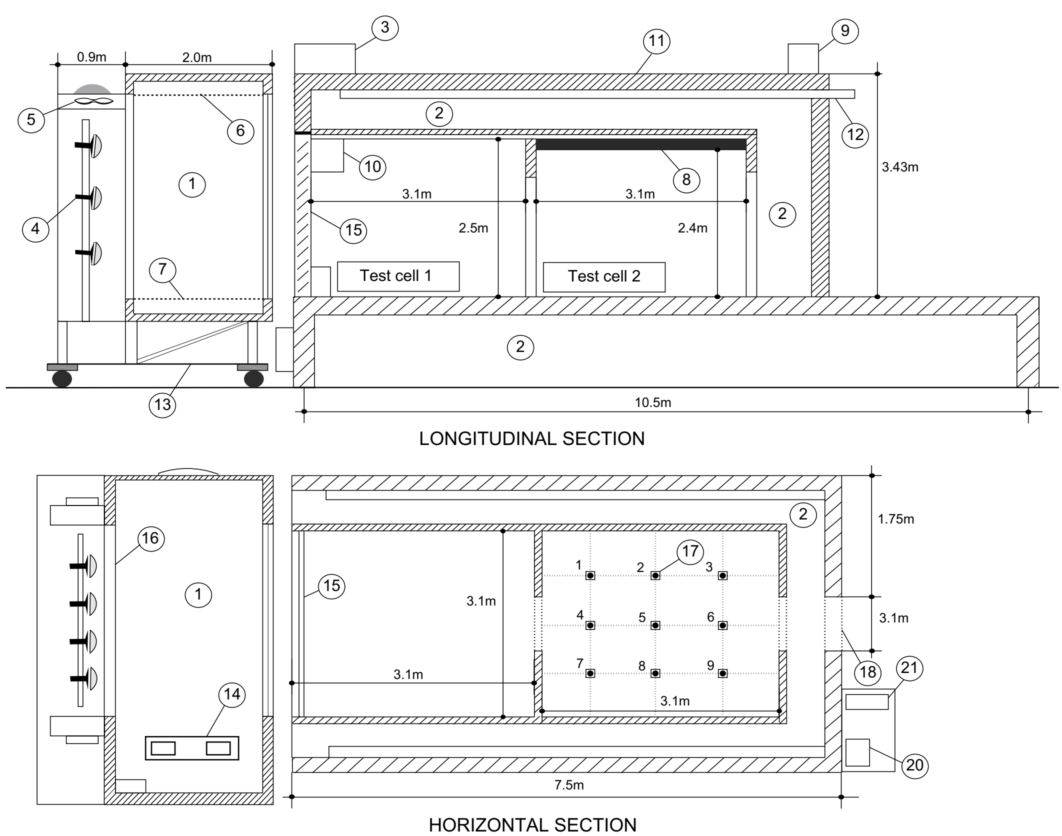

Fig. 1. Test cell facility sections. (1) climatic chamber (2) thermal guard (3) thermal guard system (4) spotlights (5) lighting system ventilation (6) supply air (7) air extraction area (8) radiant cooling ceiling system (RCC) (9) air-water heat pump (10) air diffusser (11) insulated concrete (12) air pipe (13) mobile platform (14) climatic chamber air treatement system (15) double-skin facade (16) glazed area (17) RCC surface temperature probes (Pt100) (18) exterior door (19)electric system of spotlights (20) data acquisition system (21) computer.