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Thermal environment in a simulated double office room with convective and radiant cooling systems

Panu Mustakallio [a, *], Zhecho Bolashikov [b], Lauris Rezgals [c], Aleksandra Lipczynska [d], Arsen Melikov [c], Risto Kosonen [e]

[a] Halton Oy, Haltonintie 1-3, 47400 Kausala, Finland
[b] NIRAS, Building and Industry East, Sortemosevej 19, 3450 Allerød, Denmark
[c] International Centre for Indoor Environment and Energy, DTU Civil Engineering, Technical University of Denmark, Nils Koppels Alle, Building 402, 2800 Lyngby, Denmark
[d] Department of Heating, Ventilation and Dust Removal Technology, Silesian University of Technology, Gliwice, Poland
[e] Department of Mechanical Engineering, Aalto University, Sähkömiehentie 4, 02150 Espoo, Finland

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ABSTRACT

The thermal environment in a double office room obtained with chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and overhead mixing total volume ventilation (MTVV) under summer (cooling) condition was compared. Design (peak) and usual (average) heat load from solar radiation, office equipment, lighting and occupants was simulated, respectively at 62 W/m^2 and 38 W/m^2 under four different workstation layouts. Air temperature, globe (operative) temperature, radiant asymmetry, air velocity and turbulent intensity were measured and draught rate was calculated. Manikin-based equivalent temperature (MBET) was determined by using two thermal manikins. CCMV provided slightly more uniform thermal environment and the least sensitive to different workstation layouts than the other systems. CB provided a bit higher draught rate levels than CCMV especially in the design heat load cases. With CBR, the thermal environment was found to be between CB and CCMV. MTVV generated high draught level under the tested design heat load cases. All cooling systems generated similar thermal environment in the usual heat load cases. It would be recommended to include the measurement height of 0.05 m in indoor climate testing standards for obtaining more generic view of the draught risk.

1. Introduction

The design of indoor climate systems in modern office buildings should enable comfortable and productive indoor environment for occupants as well as energy efficient operation. The modern systems can provide cooling by convection, such as active chilled beams (operating by induction, i.e. cooling and mixing of induced room air with supplied clean air), or by combined convection and radiation; such as mixing ventilation (convection) combined with chilled ceiling (both radiation and convection). The main research data and design guidelines of chilled beam systems, chilled ceiling systems and mixing ventilation have been summarized in the guidebooks by Federation of European Heating, Ventilation and Air Conditioning Associations (REHVA) [1–3]. A review of the research on radiant cooling and heating systems during the last 50 years [4] reported that chilled ceiling in cooling mode has been extensively studied, but not many studies on the thermal environment achieved with chilled ceiling combined with mixing ventilation and comparison of its performance with the performance of convective systems alone have been reported.

The present standards ISO 7730 [5] and EN 15251 [6] define guidelines for design of high-class thermal environment by recommending specific comfort levels of air, mean radiant and operative temperature, air velocity, humidity, etc. for winter and summer conditions. Recently published review paper on thermal comfort generated by radiant and convective cooling systems [7]

Abbreviations: CB, Active chilled beam (chilled beam operating based on induction principle); CBR, Active chilled beam with integrated radiant panel; CCMV, Chilled ceiling combined with ceiling installed mixing ventilation terminal units; MTVV, Overhead total volume mixing ventilation; MBET, Manikin based equivalent temperature.

* Corresponding author.
E-mail address: panu.mustakallio@halton.com (P. Mustakallio).

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concluded that in general radiant systems may provide equal or better comfort compared to all-air convective systems. However there was very limited number of studies, especially field studies, reporting on occupants' feedback. Some earlier studies [8,9] did not indicate clear occupants' preference between the generated thermal environment with a chilled ceiling combined with mixing ventilation and with only mixing ventilation. At the same time other studies [10,11] reported that the generated indoor climate with radiant ceiling panel systems combined with mixing ventilation was preferred. However none of these studies analyzed the room air distribution in detail as a factor which could have had major effect on the thermal conditions.

Comprehensive measurements of the thermal environment and air distribution generated in a simulated office environment by active chilled beams, chilled beams with integrated radiant panels, chilled ceiling combined with mixing air distribution and mixing air distribution alone under cooling mode of operation has been performed and compared [8,12–18]. Results reveal that in general chilled beam, chilled beam with integrated radiant panels and chilled ceiling combined with mixing ventilation generated similar thermal environment within the occupied zone [8,12,13]. It was concluded that the heat load level played substantial role on the generated airflow pattern and characteristics of the studied systems. In practice flexibility in workstation layout is important. Full-scale test in an open plan office showed that chilled bean system provided acceptable uniformity of the thermal environment under reduced air flow rate compared to conventional air distribution systems [14]. Due to improved interaction of room airflows (ventilation flow, buoyancy flow from heated window, thermal plume generated by occupants, etc.) lengthwise installation of chilled beams in the room (perpendicular to the window wall) generates better thermal environment compared to crosswise installation, i.e. parallel to the window wall [15]. Increasing the heat load level from about 50 W/m^2 to 80 W/m^2 increased substantially the draught rate levels in the office room. The importance of room airflow interaction on the thermal environment was also found in another study with lengthwise installed exposed chilled beams when operating under different heat load levels and heat load distribution [16]. The operation of the chilled beam with regard to the supply air distribution was disturbed by convection flows when the heat load increased from 56 W/m^2 to 111 W/m^2. The room air velocity levels were acceptable with heat loads below 100 W/m^2. The important effect of buoyancy flows (warm/cold window, occupants, etc.) on the airflow pattern and velocity distribution in a room with lengthwise installed exposed chilled beams was reported in Refs. [17,18]. Areas of higher draft risk were found in the occupied zone as a result of airflow interaction.

In practice flexibility in workstation layout is important. Changing location of workstations leads to change of heat load distribution. The performance of the discussed above convective and radiant cooling systems under different heat source locations (workstation lay-outs) has not been studied. This is in the focus of the present study. The hypotheses of the present research was that the ceiling radiant cooling system combined with mixing ventilation can provide more uniform thermal conditions than only convective cooling systems (chilled beam, mixing ventilation) regardless of the workstation layout.

2. Methods

2.1. Test room

Measurements were performed in a full-scale test room (4.12 m × 4.20 m x 2.89 m, L x W x H) under steady state conditions at 26 °C target room air temperature. Four cases of office room layout with two occupants were simulated: the occupants were facing each other and sitting turned with backs to each other located close to the window and on the opposite side of the office room, Fig. 1b. Two cooling conditions were simulated: design (peak) heat load - 62 W/m^2 and usual (average) heat load - 38 W/m^2. The cases were designed according to the recommendations of EN 15251 [6] standard for category II indoor climate conditions and the generated indoor climate conditions were compared with ISO 7730 [5] category B requirements for local discomfort. Heat load from two occupants, two laptop computers, four ceiling lighting units and solar radiation were simulated. The heat load for the studied conditions is given in Table 1. Surface temperature of simulated windows (water panels) and floor surface temperature (simulated by 5 electrical heated foils connected in parallel [2.0 m × 0.75 m, L x W] below the simulated windows) was controlled to simulate the solar heat gains. Two full-sized thermal manikins with the complex body shape of an average Scandinavian woman of 1.7 m height were used to resemble two seated occupants. One of the manikins consisted of 17 body segments and the other had 23 body segments. The positioning of the heat loads in the room is shown in Fig. 1. Photos of the experimental setup with workstation layouts S1 and S3 are shown in Fig. 3.

2.2. Cooling systems

Four cooling systems were used to generate the required thermal environment in the room: Active chilled beam (CB), chilled beam with incorporated radiant panels (CBR), chilled ceiling combined with mixing ventilation (CCMV) and overhead total volume mixing ventilation (MTVV). The operating principle of the four cooling systems is schematically shown in Fig. 2. The same exposed chilled beam (total length 3.0 m and coil length 2.10 m installed 2.5 m above the floor) was used in the cases CB and CBR (Fig. 2). In the CBR case the surface area of the radiant panels was 3.6 m^2 (3.0 m (L) x 1.2 m (W)). Approximately 30% of the cooling power was delivered by the incorporated radiant panels according to the calculations based on the measurement data and the manufacturer's product data. The chilled beam was removed from the ceiling when CCMV or MTVV cases were measured. In the case of CCMV cooling panels were integrated into the suspended ceiling tiles. The chilled ceiling covered 77% (13 m^2) of the total ceiling surface. The top surface of the tiles was not insulated. Required supply air flow rate was 26 l/s in CB, CBR and CCMV cases, and was increased to 90 l/s (with design heat load) and to 55 l/s (with usual heat load) in MTVV cases to compensate for the required cooling demand. Supplied air was distributed towards the two walls, i.e. in direction parallel to the window by two linear diffusers each with two slots sized 0.472 m × 0.020 m each (Fig. 2). In the MTVV case, a third linear diffuser (located in the middle in Fig. 1a) was used due to the increased supply air flow rate.

Supply air temperature varied between 16 and 17 °C in the studied cases and it was maintained constant within the accuracy of ±0.2 °C. Water inlet temperatures varied between 15.5 and 17 °C in the studied cases with design heat load and between 20.7 and 21.7 °C with usual heat load, with return water about 1–3 °C warmer. Water mass flow rate was between 0.07 and 0.12 kg/s. In all measured cases, water inlet temperatures and water mass flow rates were constant.

2.3. Measurements

The supply air flow rate and the room air temperature (measured continuously at a reference points described in the following) corresponded to Category II with low polluting building emissions according to EN15251 [6]. The reference room air and