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Published in:

Proceedings of 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings

Publication date:

2013

[Link back to DTU Orbit](#)

Citation (APA):

Bolashikov, Z. D., Mustakallio, P., Kolencíková, S., Kostov, K., Melikov, A. K., & Kosonen, R. (2013). Thermal Comfort in Simulated Office Environment with Four Convective and Radiant Cooling Systems. In Proceedings of 11th REHVA World Congress and the 8th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings [Paper ID: 375]

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Thermal Comfort in Simulated Office Environment with Four Convective and Radiant Cooling Systems

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Abstract

Experiments with 24 human subjects in a simulated office with four cooling systems were performed. The systems were: chilled beam (CB), chilled beam with integrated radiant panel (CBR), chilled ceiling with overhead mixing ventilation (CCMV) and four desk partition mounted radiant cooling panels with overhead mixing ventilation (MVRC). Whole body thermal sensation (TS) and whole body TS acceptability under the four systems in a simulated office room for one hour exposure were collected. The simulated two-man office (4.12 x 4.20 x 2.89 m, L x W x H) was kept at 26 °C room air temperature. Moderate heat load of 64 W/m² was generated by simulated solar heat load, 2 laptops and 2 occupants, giving in total 1104 W. The supplied outdoor air temperature was kept at 16 °C. The supply air flow rate for CB, CBR and CCMV was set to 26 L/s (category II low-polluting building, EN 15251-2007). For MVRC supply airflow of 44 L/s was set in order to maintain 26 °C room air temperature. Under the studied conditions, all four systems showed similar performance with respect to whole body TS: occupants felt between “neutral” to “slightly warm” on the TS scale in EN 15251-2007. Female felt whole body TS closer to “neutral” compared to male, whose votes were closer to the “slightly warm” thermal sensation. The whole body TS acceptability was rated close to “clearly acceptable” (EN 15251-2007) and was independent of subject's gender for all tested systems.

Keywords - radiant cooling; convective cooling, mixing ventilation, human subject evaluation, thermal comfort;

1. Introduction

In contemporary buildings the heat load generated from appliances and occupants can result in elevated indoor temperatures. The well insulated building does not allow for the generated heat to sink into the envelope and outdoors. Therefore it becomes challenging for the designers and engineers to provide the thermally comfortable conditions as recommended in the present standards ISO 7730 [1] and EN 15251 [2]. Providing more air indoors can result in increased draft risk and energy penalties. Water is 4000 times more efficient to transport heat than air. Therefore water cooling systems based on radiation, convection or combination of both are becoming more and more popular, i.e. chilled ceiling, chilled beam, chilled beam with incorporated radiant panels, etc. Thermal environment in occupied spaces provided by such systems have been documented by physical measurements, [3, 4 and 5]. The results show that the generated indoor conditions result in strongly non homogeneous thermal environment. However the human thermal perception to such non-uniform environment has not been studied in details, [6] and requires further investigation. ”

The present paper reports on experiments performed with 24 human subjects in realistically simulated office room with four cooling systems under summer conditions: chilled beam (CB), chilled beam with integrated radiant panel (CBR), chilled ceiling with overhead mixing ventilation (CCMV) and four desk partition mounted radiant cooling panels with overhead mixing ventilation (MVRC). The human subject experiments were part of a set of full scale experiments including physical measurements as well. The results of the physical measurements are reported in two other papers, [7 and 8].

2. Method

A full-scale climate chamber ($L \times W \times H = 4.12 \text{ m} \times 4.2 \text{ m} \times 2.89 \text{ m}$) was set-up to simulate a real office. The room was furnished with two desks attached so that the two occupants were facing each other. On each workstation there was a laptop to simulate the heat load from office equipment and to collect the responses of the occupants to the questionnaires used. Four low energy lamps, 40 W each, were used to provide the ambient light in the chamber. Artificial windows with controlled surface temperature mimicked the impact of direct sunlight during summer season. Five heating panels were placed along the floor below the windows to generate heat and to simulate solar irradiation. The two workstations were positioned at a distance of 0.6 m from the simulated window, in the middle of the simulated solar irradiation on the floor.

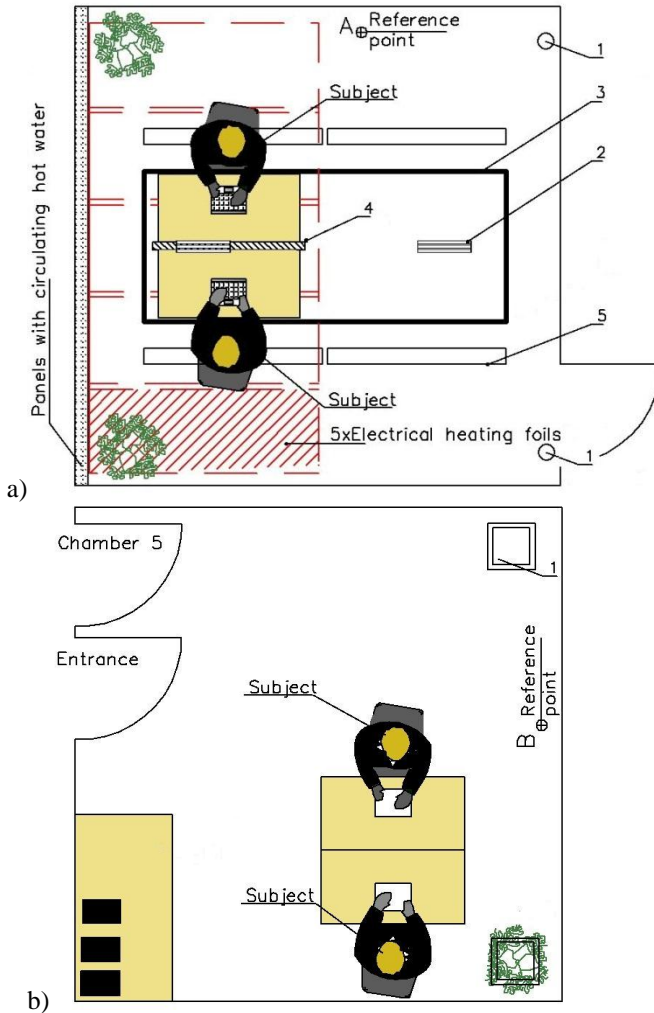


Fig. 1 Experimental set-up: a) exposure chamber; b) acclimatisation chamber.
 1) ventilation exhaust, 2) ventilation supply, 3) chilled beam (CB), 4) desk partition mounted radiant cooling panels, 5) light fixtures. In the exposure chamber on the floor below the simulated windows were positioned 5 electrical heating foils

2.1. Chilled Beam

The chilled beam tested in this study consisted of two main components: active chilled beam, with two heat exchangers alongside the plenum box, and a circuit of five hydronic radiant panels integrated in chilled beam design. A

3-way manually operated valve allowed to cut off the water flow towards the radiant panels and bypass them. The primary air, supplied from the plenum box, mixed with the entrained air and was discharged upward to flow along the ceiling before entering the occupied zone of the room.

2.2. Chilled Ceiling

The radiant ceiling consisted of 18 panels (Uponor, Comfort panels) with dimensions 1.2 m x 0.6 m. The panels were connected in 6 rows of 3 panels connected in series. The middle row of the ceiling was made of standard ceiling panels in which two air supply diffusers were installed. The ceiling area covered by the radiant panels was 12.64 m², which was 77% of the total ceiling area of 16.48 m². The air from the diffusers was discharged tangentially along the ceiling, i.e. to be in contact with the cold surface of the ceiling.

2.3. Radiant Cooling Panels

The fourth of the tested cooling systems in this experiment consisted of four single panel radiators PURMO Hygiene H10 with dimensions H=0.60 m and L=1.40 m. The radiators were attached onto a steel frame, positioned between the two workstations (desk incorporated radiant panel cooling system). Two radiators were installed at each workstation, one below the desk and one above it. The radiant cooling panels were used in conjunction with the mixing ventilation also used in the case of chilled ceiling.

2.4. Experimental Conditions

All four systems were tested under the same heat load, Table 1, simulating summer conditions under a design room air temperature of 26 °C.

Table 1. Simulated heat load in the test office room

Heat Gain	Heat Load [W]	Amount [-]	Total [W]
Window	404	-	404
Solar irradiation	270	-	270
Laptop	60	2	120
Occupants	75	2	150
Lighting	40	4	160

Four experiments named after the four cooling systems were performed, Table 2. The set points for supply water flow rate and temperature were obtained based on calculations and physical measurements performed with thermal manikins prior to the human subject experiments, [8 and 9]. Under all cases the supply room air temperature was kept at 16 °C and 26 L/s flow rate. Only with MVRC the supplied amount of outdoor air was nearly

doubled, i.e. 44 L/s. Because of the lower surface area of the radiators compared to the chilled ceiling they could not provide the same cooling capacity to the room in order to achieve 26 °C. Therefore for the MVRC higher amount of supply fresh air was needed to handle the generated heat load, Table 2. When the CCM and MVRC cooling systems were tested the chilled beam was dismantled from the ceiling and removed from the room.

Table 2. Designed operating parameters for the four cooling systems

System	Water			Air			
	Supply		Return	Supply		Return	Room
	Temp. [°C]	Flow rate [kg/s]	Temp. [°C]	Temp. [°C]	Flow rate [L/s]	Temp. [°C]	Temp. [°C]
CB	16.5	0.10	18.5	16.0	26	26	26
CBR	17.5	0.05	19.5	16.0	26	26	26
CCMV	15.5	0.10	17.5	16.0	26	26	26
MVRC	15.5	0.10	16.5	16.0	44	26	26

2.5. Subjects

Twenty-four subjects, 12 males and 12 females all healthy and non-smokers participated in the experiment. They were aged from 19 to 29 with an average age of 24 ± 4.2 .

2.6. Experimental Procedure

Each subject participated in four experiments in pairs of two subjects per condition. Upon arrival the subjects acclimatized in a neighboring room conditioned at 26 °C and with piston upward airflow for 30 min. During this time they were instructed on the experimental procedure and how to fill in the questionnaires. At the start of the acclimatization period they filled in a questionnaire about their clothing ensemble. Three times within these 30 min subject's skin temperature of the forehead and both hands was measured: upon arrival, after 20 min and just before entering the test room. No information was given to the subjects on the experimental conditions: air temperature, type of ventilation/cooling system, flow rate, etc. After 30 min the subjects entered the test room and sat at the workplaces. They filled in questionnaires every 9 minutes, the first time being immediately upon sitting. In between two sets of questionnaires the subjects did either simple multiplication tasks (two-digit number multiplied with another two-digit number) or solved Sudoku puzzle. The subjects stayed 60 min in total after that they left. During the whole experiment the participants were encouraged to modify their clothing based on their thermal preferences. The described experimental procedure was identical for all four experiments.

2.7. Questionnaires

The subjective response to the thermal environment was collected via electronic version of questionnaires programmed and installed on the two laptops, one at each workstation. The questions related to the whole body and local thermal sensation on a 7-point thermal scale [2], acceptability of the thermal sensation experienced [2], air movement sensation, preference for more, less or unchanged air movement, severity of selected SBS symptoms (i.e. eye dryness, dry throat and nose etc.) and whether or not they have changed their clothing within the last 9 minutes of the exposure.

2.8. Data Analysis

The data obtained from the questionnaires was analyzed for statistical significance among the systems with a commercially available software package Statistica 10. Each data sample of 24 values (collected from 24 subjects) was tested for normality using the Shapiro-Wilk test. The data were then compared using paired Student's t test (for normally distributed data) or Wilcoxon signed-rank test (non-parametric data).

3. Results

The current paper reports on the whole body thermal sensation vote of the subjects and how acceptable that sensation was under the four experimental cases. The individual whole body thermal sensation votes reported by the subjects are used to calculate the median thermal sensation vote (non-normal distribution of the subjective votes). The error bars are showing the 25 and 75 percentiles.

Figure 2a compares the medians for each of the four experiments with CB, CBR, CCMV and MVRC systems. As can be seen no major difference were documented among the four systems tested. All of them managed to keep the thermal sensation of subjects between “neutral” = 0 and “slightly warm” = 1. The largest amount of cooling based on the whole body thermal sensation felt from the subjects was provided with either CBR or CCMV systems, i.e. subjects felt closest to the “neutral” = 0 thermal sensation.

Figure 2b is similar to Figure 2a but here the median vote for the whole body thermal sensation is plotted as a function of the occupant's gender. In general females felt the thermal conditions with all four cooling systems cooler than males, i.e. closer to the “neutral” = 0 sensation. No significant differences were found among three of the four systems, namely CB, CCMV and MVRC. Female subjects were significantly more sensitive to the whole body cooling with CBR than males ($p < 0.05$).

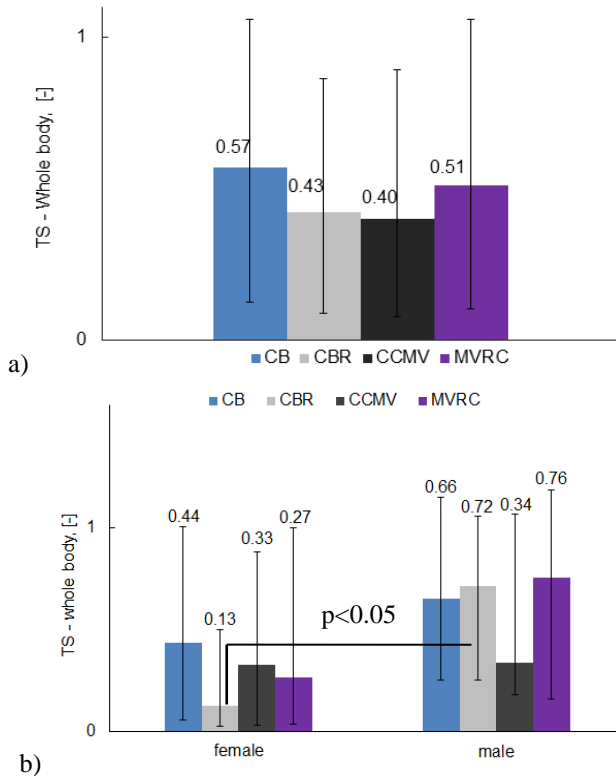


Fig. 2 Whole body thermal sensation with the studied systems, CB, CBR, CCMV and MVRC; a) median of the whole body TS over the whole exposure, b) median of the whole body TS over the whole exposure divided by gender.

The acceptability of the whole body thermal sensation experienced by the 24 participants with all four cooling systems was evaluated as being close to “clearly acceptable” = 1, Figure 3. No clear difference could be observed among the systems based on the acceptability of the whole body thermal sensation felt. However the CB and MVRC resulted in highest variations in subjects’ votes, while CBR and CCMV had less. Hence CBR and CCMV showed slightly higher potential to provide more acceptable whole body thermal sensation for occupants compared to the other two cooling systems. However to justify this hypothesis, experiments with more subjects are needed.

Both females and males rated highly the acceptability of their whole body sensation close to “clearly acceptable” = 1. No clear trend in rating the systems based on whole body TS acceptability was documented for the

female participants. However for the male subjects the highest ranked system was CCMV and lowest was MVRC.

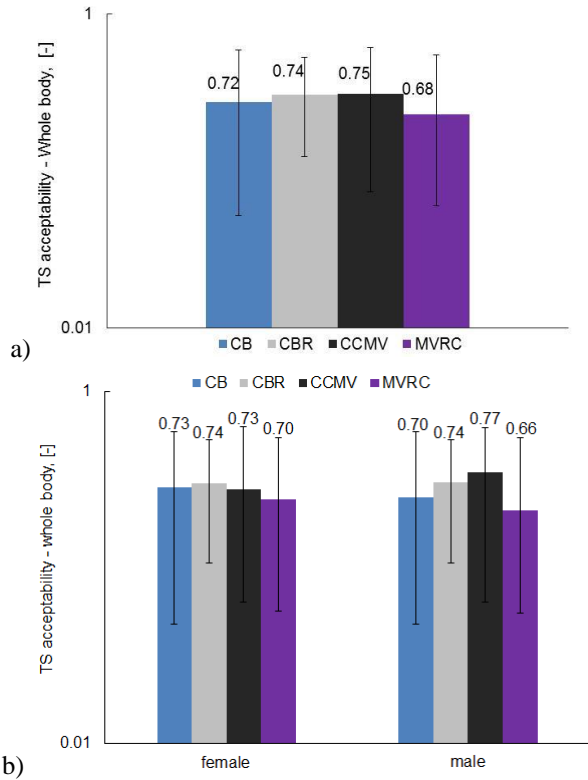


Fig. 3 Acceptability of whole body thermal sensation with the studied systems, CB, CBR, CCMV and MVRC; a) median of whole body TS acceptability over the whole exposure, b) median of the whole body TS acceptability over the whole exposure divided by gender.

4. Discussion

The present study investigated and compared human response to high temperature cooling systems, based on combined radiant and convective cooling (CBR, CCMV and MVRC) with only convective cooling (CB).

All systems managed to provide whole body thermal sensation close to the “neutral” = 0 level. CB and MVRC resulted in warmer whole body thermal sensation compared to CBR and CCMV. The 25 and 75 percentiles of the votes were in larger area around the median vote, Figure 2 and 3. This means that the generated thermal environment by CB and MVRC is more dynamic and is slightly more difficult for the people to adapt to the environment. With CBR and CCMV the majority of subjects voted closer to

the median value compared to CB and MVRC, i.e. more subjects sensed and accepted the thermal environment in a similar way when CBR and CCMV were operated. This confirms the finding that occupants in office buildings perceive better and access higher the thermal comfort provided by radiant cooling systems (chilled ceiling systems) compared to convective cooling (conventional mixing ventilation) [9].

The median acceptability of the experienced thermal sensation with all systems was in the upper part of the acceptability scale, close to “clearly acceptable” = 1. Only MVRC system was reported with slightly lower thermal sensation acceptability from all of the other three systems. This can be explained with the much localized cooling effect of the system on the human body: only the front surface of the body was cooled by the desk installed cooling radiant panels. The rest of the body was cooled only by the total volume ventilation (mixing ventilation). In this case the supply air jets of the mixing ventilation had longer throw length as a result of the increased flow rate (44 L/s) and spread further along the ceiling away from the occupied zone (seen from the visualizations performed). Therefore the subjects could not benefit from the convective cooling effect of the air flow and their whole body TS was the same or felt event slightly warmer compared to the CCMV and CBR systems. However the total amount of air with CB and CBR (primal and induced) was almost twice the one supplied by the mixing alone in conjunction with MVRC. Hence the convective cooling provided by the CB or CBR was more effectively distributed within the occupied zone. Furthermore CBR provided additional cooling by radiation right above the occupied zone. Obviously the cooling effect provided by the radiant panels in the MVRC system was not enough. More radiant cooling can be provided to the occupant if the cooled surface area is increased, i.e. by installing more radiant panels above and/or beside the occupants. Further tests with the MVRC system are required to evaluate the optimal cooling performance and possibilities.

Earlier studies showed that women feel more uncomfortable than men at both high and low temperature extremes or cooler than men at low temperatures [10 and 11]. In the present study the subjects were not exposed to extreme temperatures and yet female subjects felt slightly cooler compared to male subjects with all 4 systems. However this did not affect adversely to the acceptability of the whole body thermal sensation of the females whose votes were closer to “clearly acceptable” compared to male.

5. Conclusions

The following conclusions are made:

- The studied systems, CB, CBR, CCMV and MVRC, provided enough cooling to keep the whole body and local thermal sensation close to the neutral sensation at moderate heat load of 64 W/m^2 and ambient air temperature of $26 \text{ }^\circ\text{C}$.

- Whole body thermal sensation acceptability was close to “clearly acceptable” with all four tested systems.
- Under the generated thermal conditions with CB and MVRC the whole body thermal sensation and its acceptability as reported by the subjects varied in wider ranges compared to the thermal conditions generated by CBR and CCMV, suggesting more homogeneous thermal environment within the occupied zone with CBR and CCMV.
- Female subjects were more sensitive to the generated thermal environment with any of the 4 systems tested than male subjects. However this did not affect the acceptability of their whole body thermal sensation.

6. Acknowledgement

The study is supported by Technology Agency of Finland (TEKES) in RYM-SHOK research program

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