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# EXPERIMENTAL COMPARISON OF THREE INDOOR THERMAL ENVIRONMENT CONTROL METHODS: DIFFUSE CEILING VENTILATION, CHILLED BEAM SYSTEM AND CHILLED CEILING COMBINED WITH MIXING VENTILATION

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## SUMMARY

Thermal environments created by diffuse ceiling ventilation (DCV), chilled beam system (CB) and chilled ceiling with mixing ventilation (CCMV) were compared at different heat loads. Experiments were carried out in two test rooms (4.1 x 4.2 x 2.9 $m^3$ and 5.5 x 3.8 x 3.2 $m^3$, L x W x H). A double office layout where workstations were located in the perimeter area was investigated. The heat load was increased from a usual level of 38-40 W/floor-$m^2$ to a peak load level of 57-64 W/floor-$m^2$. Air temperature in the occupied zone was kept at 26 ± 0.5°C. Air velocity and temperature were measured with omnidirectional anemometers. Mean air speed, draught rate and temperature differences were all low at the usual load and increased slightly at peak load. The CB system produced more locations with draught rates higher than 10% than the CCMV or DCV systems. Thus, the study suggests using radiant systems with air distribution to reduce draught discomfort in the modern indoor environments.

**Keywords**: thermal environment, heat load, buoyancy flows, airflow interaction, air distribution

## 1 INTRODUCTION

The concept of thermal comfort was originally defined to satisfy the human desire to feel thermally comfortable (Fanger, 1970). This definition has inspired several studies towards improving the knowledge and understanding of satisfaction within different thermal environments throughout the past five decades. Recently, local thermal comfort has been found to be a common complaint in various public buildings (Kosonen et al., 2011; Cao et al., 2012; Mustakallio et al., 2016). The room airflow pattern in cooling conditions depends on the relative locations of air distribution units and heat sources (Koskela et al., 2010). Consequently, one of the main challenges in modern offices is to distribute clean air to the workstations in an energy efficient manner without increasing the draught risk.

Draught is often defined as unwanted local convective cooling of a person (Fanger, 1970). The draught risk increases when the airflow temperature decreases and the mean velocity and turbulence intensity increase (Müller et al. 2013). In this sense, radiant and convective cooling methods play a major role when responding to temporal and spatial airflow changes in modern user-centric environments. Furthermore, advanced personalized air distribution methods can improve thermal comfort and energy efficiency (Melikov, 2016).

In this study, diffuse ceiling ventilation (DCV), chilled beam system (CB) and chilled ceiling combined with mixing ventilation (CCMV) were compared. The main objectives were to investigate the effects of usual and peak heat loads on thermal conditions and discomfort caused by draught. The main hypothesis was that combining radiant and convective cooling (i.e. CCMV system) could improve the thermal comfort by reducing draught. Air temperature, air speed and draught rate in the occupied zone were all compared. The novelty of this study comes from the comparison of the aforementioned state of the art air conditioning systems at typical heat load levels.

## 2 METHODS

Experiments were carried out in two test chambers under stable thermal conditions (Figure 1). The first set of measurements (CCMV + CB) was made at the Technical University of Denmark and the DCV measurements were conducted at Aalto University in Finland. The internal dimensions of test chamber 1, where the CCMV and CB systems were studied, were 4.1 m (length), 4.2 m (width) and 2.9 m (height) (Mustakallio et al., 2016). The corresponding dimensions of test chamber 2, where the DCV system was studied, were 5.5 m (length), 3.8 m (width) and 3.2 m (height). The test cases are shown in Table 1. The usual heat load was 8% higher and the peak load was 11% lower with the DCV than with the CCMV and CB systems, respectively.

*Table 1. Test case parameters at the test chambers.*

| Test chamber 1: CB,CCMV | Usual load | Peak load | Test chamber 2: DCV | Usual load | Peak load |
|---|---|---|---|---|---|
| Floor area, $m^2$ | 17.3 | 17.3 | Floor area, $m^2$ | 21.0 | 21.0 |
| Heat load, W/floor-$m^2$ | 37 | 64 | Heat load, W/floor-$m^2$ | 40 | 57 |
| 2 x Thermal manikin, W | 156 | 156 | 2 x Test dummy, W | 176 | 176 |
| 2 x computer, W | 130 | 130 | 2 x computer, W | 96 | 96 |
| 2 x monitor, W | 0 | 0 | 2 x monitor, W | 70 | 70 |
| Lighting, W | 160 | 160 | Lighting, W | 116 | 116 |
| Solar-load at window, W ~ | 202 | 404 | Solar-load at window, W ~ | 381 | 317 |
| Solar-load at floor, W | 0 | 250 | Solar-load at floor, W | 0 | 420 |
| Total heat load, W | 648 | 1100 | Total heat load, W | 839 | 1195 |
| Supply airflow rate, l/s,$m^2$ | 1.5 | 1.5 | Supply airflow rate, l/s,$m^2$ | 3.6 | 5.2 |
| Supply air temperature,°C | 16 | 16 | Supply air temperature,°C | 17 | 17 |
| Room air temperature,°C | 26 | 26 | Exhaust air temperature,°C | 26 | 26 |
| Supply air cooling, W/floor-$m^2$ | −18 | −18 | Supply air cooling, W/floor-$m^2$ | −40 | −57 |
| Cooling demand from water | −19 | −46 | Cooling demand from water | 0 | 0 |

A double office layout located at the perimeter area 0.6 m away from the heated window panels was studied in both test chambers (Figure 1). In test chamber 1, each workstation consisted of a thermal manikin and a laptop. In test chamber 2, test dummies were used instead of manikins and a monitor was added to each workstation. In the CCMV system, the cooling panels were integrated into the suspended ceiling tiles. The chilled ceiling covered 77% of the total ceiling area. The top surface of the tiles was not insulated. Thus, the chilled ceiling transferred heat also above the suspended ceiling. Two linear diffusers were used to distribute the supplied air in two directions (each 0.472 m x 0.020 m). In the CB system, an exposed chilled beam with a total length of 3.0 m and a coil length of 2.1 m was installed at the height of 2.5 m. In the DCV system, a uniformly perforated suspended ceiling was used to bring supply air down to occupied zone. The perforation rate was 0.50 % of the total ceiling area and the nozzles had a diameter of 14 mm each. The nozzle rows closest to walls were sealed. In test chamber 1, the air was extracted from near the corridor wall at the height of 2.5 m by using one valve at each corner (Figure 1a). In test chamber 2, the air was extracted from the ceiling at the height of 3.2 m near location 11 (Figure 1b).

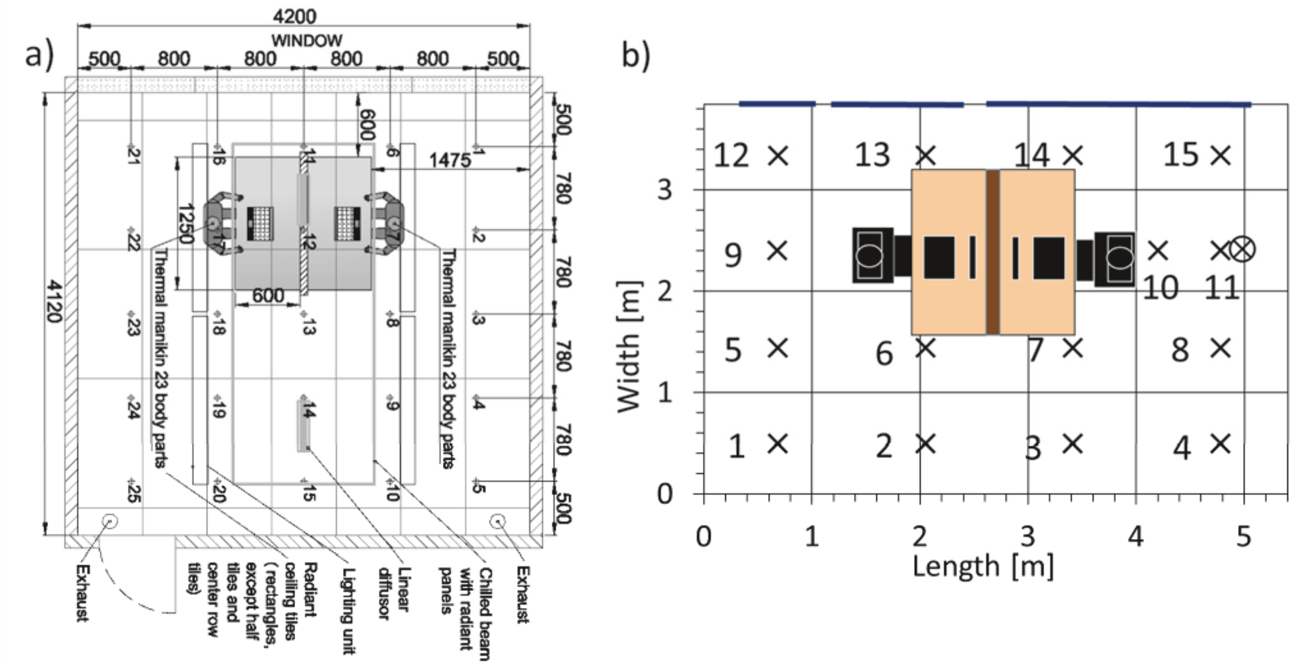


*Figure 1. a) Test chamber 1 with CB and CCMV and b) test chamber 2 with DCV.*

The omnidirectional anemometers were installed at the heights of 0.1 m, 0.6 m, 1.1 m, and 1.7 m recommended in the standard EN ISO 7726:2001 (CEN, 2001). In test chamber 1, the anemometers had an accuracy of ± 0.02 m/s ± 1% of the reading at the range of 0.05-0.5 m/s. In test chamber 2, the three lowest anemometers had an accuracy of ± 0.01 m/s ± 2.5% of the reading and the highest anemometer had an accuracy of ± 0.02 m/s ± 1.5% of the reading. The measurement duration was 5 min for the CB and CCMV systems, and 1 h for the DCV system. The variables considered in the study were air temperature, air speed and draught rate (CEN, 2005) which can be expressed as

$$DR = \left(34 - t_{a,l}\right)\left(\overline{U}_{a,l} - 0.05\right)^{0.62}\left(0.37 \cdot \overline{U}_{a,l} \cdot Tu + 3.14\right), \quad (1)$$

where $t_{a,l}$ [°C] is the local air temperature, $\overline{U}_{a,l}$ [m/s] is the local mean air velocity, and $Tu$ [%] is the local turbulence intensity. The measurement uncertainty was 0.2°C for the air temperature and 5% p.p. for the draught rate (Melikov et al., 2007).

## 3 RESULTS

### 3.1 Air temperature

The air temperature measurements are summarized in Table 2. The average of local mean air temperatures was quite similar with all systems. However, the range was largest with the DCV and smallest with the CCMV at the usual heat load conditions. At the peak load conditions, the situation changed with the CCMV having the largest and CB the smallest range. The standard deviation was the same for all systems at the usual load. However, at the peak load, the deviation increased and the largest deviation was obtained with CCMV and smallest with DCV. The horizontal temperature difference between the perimeter area and the corridor side was largest with CCMV and smallest with DCV at both heat load levels. With the usual heat load, the differences were between 0.5-0.7°C and in the peak load conditions between 0.8-1.1°C. Furthermore, the vertical air temperature differences were quite similar with all systems. These differences were slightly larger (between 0.1-0.4°C) in the usual load conditions than in the peak load conditions (0.0-0.3°C). To summarize, there were no significant differences in the temperature profiles between the different systems.

*Table 2. Summary of the average air temperature results.*

| Double office layout | Usual heat load | | | Peak heat load | | |
|---|---|---|---|---|---|---|
| | CCMV | CB | DVC | CCMV | CB | DVC |
| Average air temperature [°C] | 26.0 | 25.8 | 25.6 | 26.1 | 25.8 | 25.9 |
| Standard deviation of air temperature [°C] | 0.3 | 0.3 | 0.3 | 0.6 | 0.5 | 0.4 |
| Range of mean air temperatures [°C] | 1.3 | 1.4 | 1.7 | 2.7 | 1.8 | 2.1 |
| Std. dev. / avg [%] | 1.2 | 1.2 | 1.0 | 2.3 | 1.9 | 1.5 |
| Range / avg [%] | 5.0 | 5.4 | 6.8 | 10 | 7.0 | 8.0 |
| Std. dev. / range [%] | 23 | 21 | 15 | 22 | 28 | 19 |
| difference between window to corridor sides at height 1.1 m [°C] | 0.7 | 0.6 | 0.5 | 1.1 | 1.0 | 0.8 |
| difference of heights between 0.1 m to 1.7 m [°C] | 0.3 | 0.4 | 0.1 | 0.0 | 0.3 | 0.1 |

### 3.2 Air speed

The air speed results are summarized in Table 3. The average air speeds were quite similar with all the studied systems. The maximum air speeds at the usual load were 0.27 m/s with the CB, 0.25 m/s with the DCV and 0.23 m/s with the CCMV. At the peak load conditions, the difference was slightly larger; the maximum air speeds were 0.29 m/s, 0.30 m/s and 0.24 m/s, respectively.

The standard deviation ranged from 31 to 42% of the average air speed level, with the CCMV being the lowest and DVC the highest. This indicates that the CCMV creates a slightly more stable airflow field than the other systems. Furthermore, the average air speed was lower on the window side than on the corridor side of the room. This indicates a circulating airflow pattern from the heat sources to the other side of the room which was also observed with marker smoke visualisation.

A smaller number of high air speed (>0.2 m/s) locations was obtained with the CCMV than with the other systems. However, at the peak load conditions, the CCMV and the CB were really close to each other. The largest value was observed with CB at the usual load and with DCV at the peak load. This closely follows the supply airflow rates which were the largest with DCV. All in all, the air velocities were slightly smaller with the CCMV system that with the CB and DVC systems.

*Table 3. Summary of the air speed results.*

| Double office layout | Usual heat load | | | Peak heat load | | |
|---|---|---|---|---|---|---|
| | CCMV | CB | DVC | CCMV | CB | DVC |
| Average air speed [m/s] | 0.11 | 0.12 | 0.11 | 0.13 | 0.13 | 0.14 |
| Standard deviation of air speed [m/s] | 0.04 | 0.05 | 0.05 | 0.04 | 0.05 | 0.06 |
| Max. air speed [m/s] | 0.23 | 0.27 | 0.25 | 0.24 | 0.29 | 0.30 |
| Std. dev. / avg [%] | 36 | 42 | 41 | 31 | 38 | 42 |
| Avg. air speed in window side [m/s] | 0.10 | 0.09 | 0.11 | 0.13 | 0.12 | 0.13 |
| Avg. air speed in corridor side [m/s] | 0.14 | 0.14 | 0.12 | 0.17 | 0.14 | 0.16 |
| Percentage of measurement points where air speed higher than 0.2 m/s [%] | 3 | 11 | 5 | 8 | 9 | 13 |

### 3.3 Draught rate

The draught rate results are summarized in Table 4. The average draught rate was below 10 % in the studied cases except for the CB system at the peak load. The standard deviation was smallest with the CCMV, indicating more uniform conditions. The largest maximum draught rate was measured with CB and the smallest with CCMV. The range of maximum draught rates was 13-18 % at the usual load and 16-21 % at the peak load. Consequently, the results indicate category B defined by EN ISO 7730 (CEN, 2005) for all the studied systems besides CB at the peak load conditions which falls into category C.

The draught rate was smaller on the window side than on the corridor side. This indicates the existence of airflow patterns from the heat sources to the other side of the room. The maximum draught rates were at a similar level with all the studied systems. However, the number of locations with draught rates below 10 % was the smallest with CCMV and the largest with CB. In addition, relatively high draught rates were obtained with the DCV, although the momentum flow of the supply air was low. This indicates that buoyancy flows are dominant and radiant cooling may decrease the draught discomfort more efficiently than convective cooling.

*Table 4. Summary of the draught rate results.*

| Double office layout | Usual heat load | | | Peak heat load | | |
|---|---|---|---|---|---|---|
| | CCMV | CB | DVC | CCMV | CB | DVC |
| Average draught rate [%] | 6 | 8 | 7 | 8 | 10 | 9 |
| Standard deviation of draught rate [%] | 3 | 5 | 4 | 3 | 5 | 5 |
| Max. draught rate [%] | 13 | 18 | 18 | 16 | 21 | 19 |
| Std. dev. / avg [%] | 49 | 59 | 57 | 42 | 48 | 52 |
| Avg. draught rate in window side [%] | 5 | 4 | 6 | 7 | 7 | 8 |
| Avg. draught rate in corridor side [%] | 8 | 9 | 8 | 11 | 10 | 11 |
| Percentage of measurement points where *DR* higher than 10% [%] | 6 | 33 | 15 | 31 | 41 | 35 |

## 4 DISCUSSION

The idea behind this study was to compile and compare results from measurements of different thermal environment control systems conducted in two separate laboratories. As the measurements had already been done, there were some differences between the cases. Firstly, thermal conditions were slightly different between DCV and the other systems. In addition, the measurement period was longer for the DCV than for the CCMV and CB systems. However, neither of these differences had any significant impact on the results as the total heat load levels were very close between the cases and thus a valid comparison between the systems could be made.

The results show that all the systems provided similar performance between the perimeter area and the corridor side of the room. Furthermore, the vertical air temperature differences were also quite similar. Thus, there were no significant differences in temperature profiles with the studied systems. However, the results indicate that the CCMV, including the radiant system, produced a smaller number of locations with draught rates above 10% than the other studied systems at usual load conditions. This confirms the original hypothesis and is an important finding for the future. However, in the peak load conditions, the corresponding numbers for all systems were closer to each other than with the usual load.

It seems that low-momentum convective cooling with DCV leads to similar air speed levels as e.g. the convective cooling with CB system. This is due to the domination of buoyancy flows in the flow field and their interaction with convective cooling flows, which increases with increased heat load.

None of the studied systems achieved the category A defined by EN ISO 7730 (CEN, 2005) even with the usual heat load. However, since the draught rate measurement uncertainty can be as high as 5% p.p, there is also uncertainty in the category assessment as the category boundaries are only 10% apart from each other. It is entirely possible that repeating the set of measurements would put CCMV into category A at the usual load and all systems into category C at the peak load, for example.

## 5 CONCLUSIONS

The spatial temperature differences were small between the studied systems. The maximum air temperature difference was around 1°C between the window side and the corridor side.

The maximum air speed was slightly lower with CCMV than with CB or DCV at the peak load conditions. At the usual heat load there were next to no differences in maximum air speeds between the systems.

The results indicate that the CB system caused slightly higher draught discomfort levels than the CCMV and DCV systems. The number of locations with draught rates over 10 % was very different between the systems. The system with the smallest number of locations with a *DR* higher than 10 % was CCMV.

Overall, the study suggests using a radiant system combined with an air distribution system in modern indoor environments to minimize the draught discomfort. None of the studied systems achieved the category A defined by EN ISO 7730. However, all the systems can fulfill the demands of category B except for CB which falls to category C at peak load conditions.

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