Thermal Conditions in a Simulated Office Environment with Convective and Radiant Cooling Systems

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Abstract

The thermal conditions in a two person office room were measured with four air conditioning systems: chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and four desk partition mounted local radiant cooling panels with mixing ventilation (MVRC). CB was based on convection cooling while the remaining three systems (CBR, CCMV and MVRC) on combined radiant and convective cooling. Measurements were performed in design (64 W/m^2) and usual (38 W/m^2) cooling conditions. Air temperature, operative temperature, radiant asymmetry, air velocity and turbulent intensity were measured and draft rate levels calculated in the room. Manikin-based equivalent temperature (MBET) was determined by two thermal manikins to identify the impact of the local thermal conditions generated by the studied systems on occupants' thermal comfort. The results revealed that the differences in thermal conditions between the four systems were not significant. This result was contrary to the expectation that operative temperature would be lower in the CCMV case. The velocity levels in the occupied zone were slightly higher in both CB and CBR cases. However the highest measured values were located outside the workstations.

Keywords – chilled beam; chilled ceiling; radiant cooling; convective cooling; mixing ventilation

1. Introduction

Thermal conditions in two person office room were measured with four air conditioning systems: chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixing ventilation (CCMV) and four desk partition mounted local radiant cooling panels with mixing ventilation (MVRC). CB was based on convection cooling while the remaining three systems (CBR, CCMV and MVRC) on combined - radiant and convective cooling. Thermal comfort experiments with human subjects in the studied conditions are presented in the separate paper. Also measurements of thermal conditions in 6-person meeting room are presented in other paper with CB, CBR and CCMV systems.

In earlier research, indoor climate conditions of office room full-scale test, generated with radiant ceiling panels and mixing ventilation by using radial ceiling diffuser were compared to purely convective cooling system with active chilled beam mounted into ceiling [1,2]. This study adds to the earlier performed office room radiant and convective cooling research with more comprehensive test of thermal conditions and subjective (human subject) evaluations.

2. Methods

Measurements were performed in climate chamber (4.12 x 4.20 x 2.89 m, L x W x H) in steady state conditions at 26 °C design room air temperature with 64 W/m^2 (design cond.) and 38 W/m^2 (usual cond.) heat loads generated from two occupants, computers, lighting units, and solar heat load on simulation window and on the floor. Heat balance is presented in Table 1. The impact of the local thermal conditions generated by the systems on occupants' thermal comfort was determined by two thermal manikins.

Table 1. Heat balance in measured cases

Heat balance of office room test in	Maximum cooling conditions		Usual cooling conditions	
Occupants (about 78 W/occupant)	2	persons	2	persons
	156	W	156	W
	9	W/m²	9	W/m²
Computers (about 65 W/computer)	2	computers	2	computers
	130	W	130	W
	8	W/m²	8	W/m²
Lighting	160	W	160	W
	9	W/m²	9	W/m²
Solar load - window surface temperature	34	degC	30	degC
with 6.3 m2 window and 26 degC room ~	404	W	202	W
Solar load - direct solar load on the floor	250	W	0	W
Total solar load	38	W	12	W
Total heat loads	1100	W	648	W
	64	W/m²	38	W/m²
Supply air flow rate	26	l/s	26	l/s
Supply air temperature	16	degC	16	degC
Supply air cooling power in 26 degC room	312	W	312	W
	18	W/m²	18	W/m²
Cooling power demand from water	788	W	336	W
	46	W/m²	20	W/m²

Air temperature, operative temperature, velocity and turbulent intensity were measured and draft rate levels calculated at 8 heights (0.05/0.1/0.3/0.6/ 1.1/1.7/2.0/2.4 m from floor) in the room. Measurement pole locations and test set-up is shown in Fig. 1. Surface temperatures, radiant temperature asymmetry and manikin-based equivalent temperatures [3] were measured also. In MVRC cases measurements were done only with thermal manikins. Air temperature and operative temperature sensors were of a thermistor type with accuracy of ±0.2 °C [4]. Air temperature was measured with radiation shielded sensors. Velocity sensors were of a omnidirectional hot-wire anemometer type with accuracy of ±0.2 m/s or ±1% of the reading 0.05-0.5 m/s. Measurement results were 5 minutes average readings.

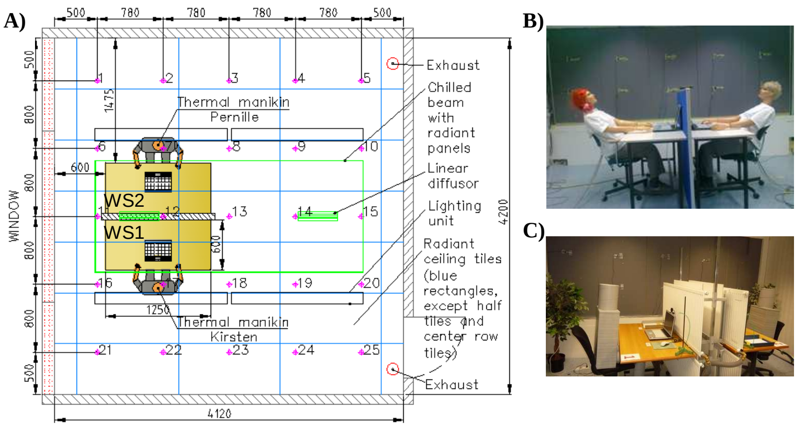

Fig. 1 A) Top view of the test room with measurement pole locations, B) photograph of the measurement setup in CB, CBR and CCMV cases and C) photograph of the measurement setup in MVRC case (thermal manekins above were used in actual measurements)

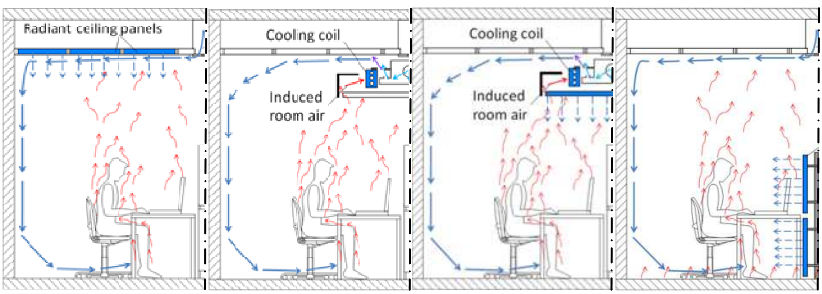

Fig. 2 Operating principle of the four cooling systems (from left): CCMV, CB, CBR and MVRC. Note: Only half of the room is shown with symmetry line on right side.

Measurements were done with the four different cooling systems described in Fig. 2. Radiant ceiling was Uponor Comfort panel system integrated into the false ceiling tiles. Radiant ceiling covered maximum 77% of the total ceiling surface, top surface of the tiles was not insulated. Supply air was distributed with two Halton SLN-472 linear diffusers. Supply air temperature in all cases was 16 °C and water inlet temperature 15 °C with return water 2-3 °C warmer. Halton CBR-2700-2100 chilled beam was used in both CBR case and CB case without water circulation in panels. Radiant panel surface area in chilled beam was 3.6 m². Chilled beam was removed from ceiling when chilled ceiling cases were measured. Prototype of personal radiant panels was set-up of Rettig panel radiators PURMO Hygiene H10 in MVRC cases. Supply air volume flow was increased in MVRC cases to compensate the missing cooling power from panel radiators.

3. Results

The measured distribution of air velocity and temperature, difference between operative and air temperature and draft rate are shown in Figs. 5-8. The measurements are readings from each available measurement pole location with design heat load conditions in upper set of floor plans and usual conditions in the lowest set in each figure. In vertical direction different measurement heights are presented and in horizontal direction different cooling systems. Only heights 0.1 m, 1.1 m and 1.7 m are presented in the figures. Average values of measurements results have been presented in Table 2 for overview of the thermal conditions.

Table 2. Average values of measurement results

OFFICE ROOM IN DESIGN (WITH BOLD FONT) AND USUAL CONDITIONS (WITH NORMAL FONT)

Measurement results in occupied zone at heights 0.1 m - 1.7 m	Chilled ceiling with mixing vent.	Chilled beam	Chilled beam with radiant panels
Average air velocity [m/s]	**0.13**	**0.13**	**0.12**
	0.11	0.12	0.11
Average of 5 highest velocities	**0.22**	**0.25**	**0.23**
	0.20	0.25	0.25
Average air temperature [°C]	**26.1**	**25.8**	**26.1**
	26.0	25.8	25.9
Average temperature of window side	**26.8**	**26.4**	**26.9**
	26.4	26.2	26.4
Average temperature of door side	**25.7**	**25.4**	**25.7**
	25.7	25.6	25.7
Average horizontal temperature diff.	**1.1**	**1.0**	**1.2**
	0.7	0.7	0.7
Average vertical temperature diff.	**0.0**	**0.3**	**0.2**
	0.3	0.4	0.2
Horizontal operative temperature diff.	**1.6**	**1.4**	**1.5**
	0.8	0.9	0.9
Vertical operative temperature diff.	**-0.1**	**0.5**	**0.2**
	0.3	0.5	n.a.
Average operative-air temperature	**0.13**	**0.29**	**0.19**
	0.12	0.13	0.10
Average draft rate [%]	**7.9**	**9.5**	**8.1**
	5.7	7.8	6.9
Average of 5 highest draft rates	**14.3**	**18.9**	**17.1**
	11.7	17.4	16.2

Manikin-based equivalent temperatures of selected body segments of the 23-body segment thermal manikin in both workstations are shown in Figs. 3-4.

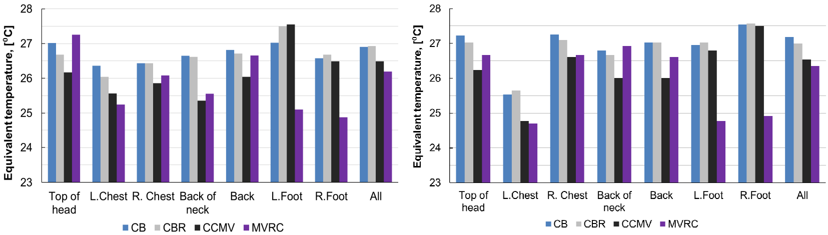

Fig. 3 Office room in design cooling conditions with Kirsten in WS1(left side) and WS2(right)

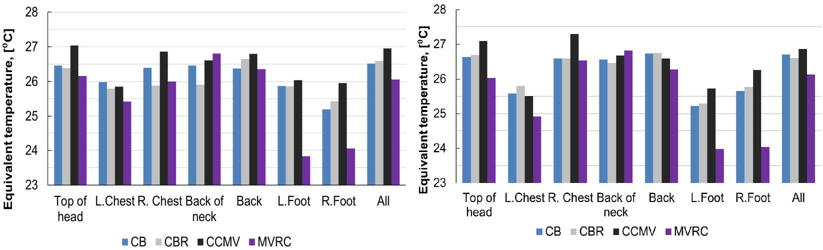

Fig. 4 Office room in usual cooling conditions with Kirsten in WS1(left side) and WS2(right)

4. Discussion

Thermal conditions with all studied systems were very similar and similar behavior of the air distribution can be seen in all cases with supply air jets turning towards the wall opposite to simulated window.

The average draft rate difference in measurement pole readings was small, 1-2% higher in CB cases and the average of five highest readings was about 5% higher in CB cases than in CCMV cases. The effect of using radiant panels integrated chilled beam can be seen slightly in the draft rate results, in CBR case, average draft rate was 0.2-1.2% higher and top five draft rates 2.8-4.5% when comparing to the CCMV case. With usual heat loads, draft rates got smaller for all systems. This was most pronounced in the CCMV case.

Average room air velocities were similar with all systems, top five highest velocities were on the range of 0.20-0.25 m/s.

Average room air temperature and operative temperature was nearly the same with all cooling systems. There were very small differences in how much operative temperature differed from air temperature between cases/systems. Average operative temperature was only 0.2 °C cooler in CCMV case than in CB case (maximum about 0.4 °C smaller). In the case with chilled beam integrated with radiant panel, maximum difference was yet smaller (about 0.2 °C). This was still very near the accuracy of the sensors.

There was quite significant horizontal temperature difference between window side and door side of the room (in design conditions 1.0-1.2 °C and in usual 0.7 °C). Horizontal operative temperature difference was even bigger (1.4-1.6 / 0.8-0.9 °C) due to the one-sided locations of the heat loads.

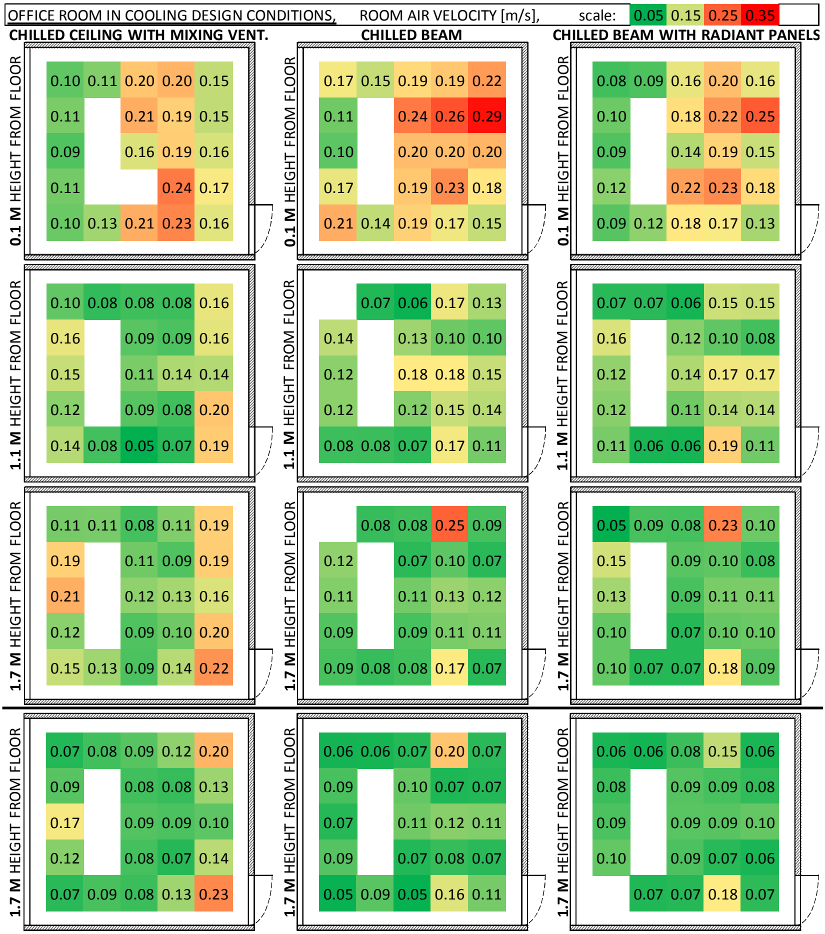

Fig. 5 Measured air velocity distribution. Three charts from top in design cooling conditions at 0.1 m, 1.1 m and 1.7 m, and lowest charts in usual conditions at 1.7 m height from floor.

Due to the horizontal temperature difference, the air and operative temperature near the window was about 0.4-0.9 °C higher than room design temperature (in the middle) in all cases.

Vertical temperature difference in the room in all cases was very small (-0.1-0.5 °C), with radiant systems a bit smaller. In the design cooling case the difference can be seen most clearly.

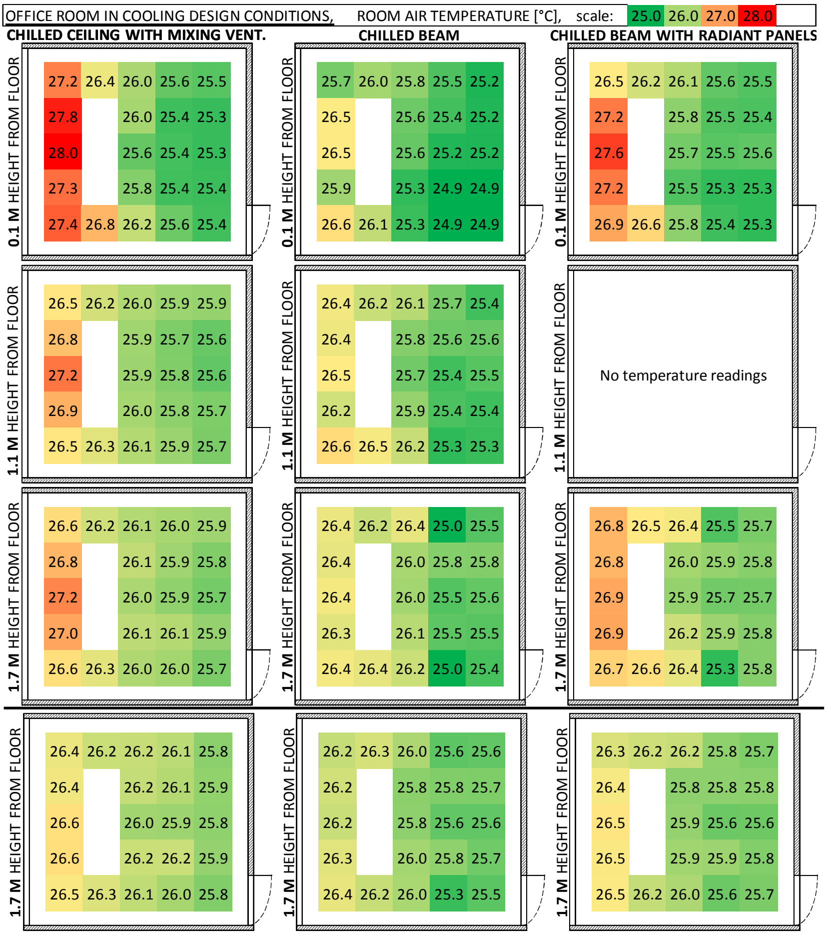

Fig. 6 Measured air temperatures. Three charts from top in design cooling conditions at 0.1 m, 1.1 m and 1.7 m, and lowest charts in usual conditions at 1.7 m height from floor.

Main difference in equivalent temperatures with different cooling systems was that in design conditions difference was logical with slightly lower temperatures in CCMV case. In usual conditions for some reason equivalent temperature was higher in CCMV case. This deviation should be researched further preferably with CFD-simulations, one reason could be difference in the convection flows at window side due to smaller circulation of the room flow. Still the top of the head temperature should be smaller in CCMV case.

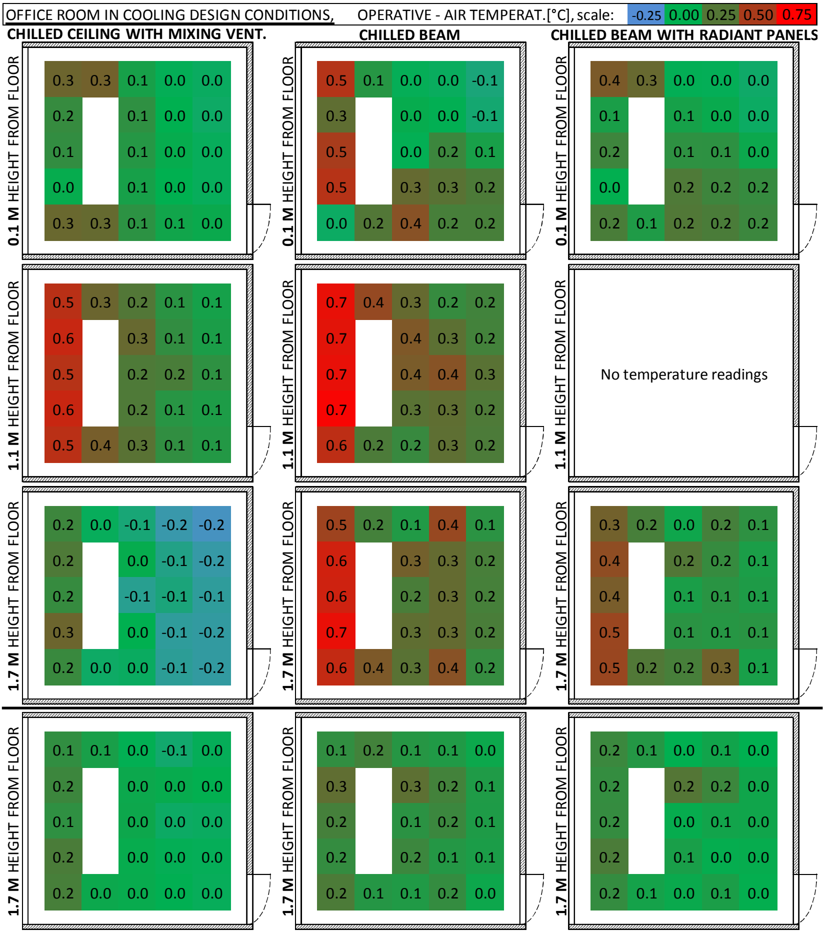

Fig. 7 Measured air temperature subtracted from operative temperature. Three charts from top in design cooling conditions at 0.1 m, 1.1 m and 1.7 m, and lowest charts in usual conditions.

MVRC system gave a bit lower equivalent temperature for most of the body segments except top of head and back. The temperature range was from

24.5 – 27 °C, a bit larger than with other systems. Especially equivalent temperatures of hands and legs at the door side (Fig. 1) were low.

In overall there was a small difference in thermal conditions between the cooling with the radiant ceiling and chilled beam system. This was quite similar than found in earlier study [1,2].

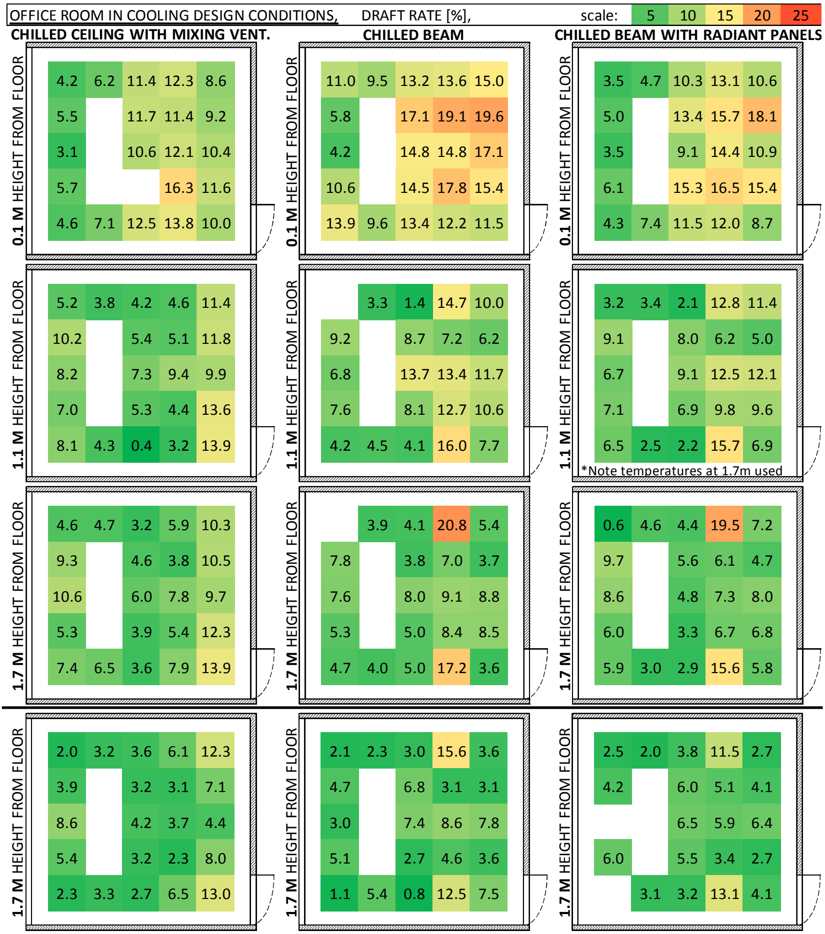

Fig. 8 Measured draft rates. Three charts from top in design cooling conditions at 0.1 m, 1.1 m and 1.7 m, and lowest charts in usual conditions at 1.7 m height from floor.

A bit higher velocities and draft rates in CB and CBR cases are caused by the bigger air volume supply by chilled beam due to the induction air circulation especially in the area at the door side (Fig. 1). This could be slightly increased by chilled beam installed exposed to ceiling in this study. The conditions in the room where occupants are located are still very similar.

Even if the effect of the radiant cooling to the operative temperature was much smaller than expected, both CCMV and CBR could provide operative temperatures a bit nearer the air temperature than CB system and a bit more uniform thermal environment. Still clear horizontal temperature gradient exists in the room that can't be avoided with any of the cooling systems. For this reason specific perimeter cooling system or workstation installed cooling system controlled by occupant could provide the most optimal thermal conditions for the office room especially near the perimeter zone.

5. Conclusions

- The results revealed that the differences in thermal conditions between the four systems were not big.
- An important finding was that air temperature and operative temperature were similar in all studied cases (operative temperature maximum only 0.2 °C lower than room air temperature).
- This result was contrary to the expectation that operative temperature would be lower in the CCMV case.
- The velocity levels in the occupied zone were slightly higher in the CB and CBR cases, however the highest measured values were located outside the workstations.

6. Acknowledgment

The study is supported by Technology Agency of Finland (TEKES) in RYM-SHOK research program, and Bjarne Saxhof Fonden.

7. References

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