Thermal comfort with radiant and convective cooling systems




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The difference in thermal conditions between convective and radiant systems is not significant. Contrary to common awareness air temperature and operative temperature are almost similar in room occupied zone with radiant ceiling and chilled beam systems. Experiments with human subjects indicate similar performance of systems with respect to the whole body thermal sensation and acceptability of thermal conditions.

Keywords: radiant cooling, convective cooling, thermal comfort, operative temperature, radiant panels.

To describe human body heat transfer, the concept of operative temperature has been introduced. The combined influence of room air temperature and mean radiant temperatures is expressed as the operative temperature. In normal conditions, air temperature and mean radiant temperature in spaces are equally important for thermal comfort. Compared to a convective cooling system a radiant surface cooling system can achieve the same level of operative temperature at a higher room air temperature. Thus, it is desirable to generate indoor conditions where operative temperature is lower than room air temperature and realise savings in energy consumption.

Providing high convective cooling capacity can result in increased draft risk. In offices where heat loads are often at the level of 60 – 100 W per floor-m², it becomes challenging for the designers to provide thermally comfortable conditions as recommended in the present standards (ISO 7730 2005 and EN 15251 2007). Water is much more efficient to transport energy than air: density and specific heat capacity of water is much higher than that of air making it 4 000 times more efficient for the same volume of fluid used. Therefore combined air-water cooling systems are well-accepted solution, i.e. chilled ceiling combined with mixing ventilation, chilled beam, chilled beam with incorporated radiant panels, etc. are nowadays commonly use in commercial buildings. Inlet water temperature of combined air-water systems is typically 14–19°C in cooling mode and 35–40°C in heating mode. Hence, these systems can utilize high temperature level of water for cooling and low temperature level of water for heating allowing to increase the total efficiency. In air-water cooling systems, heat/cold is transferred to room space based on radiation, convection or combination of both. In radiant ceiling panel, the convection and radiant are almost equal (radiation 50%

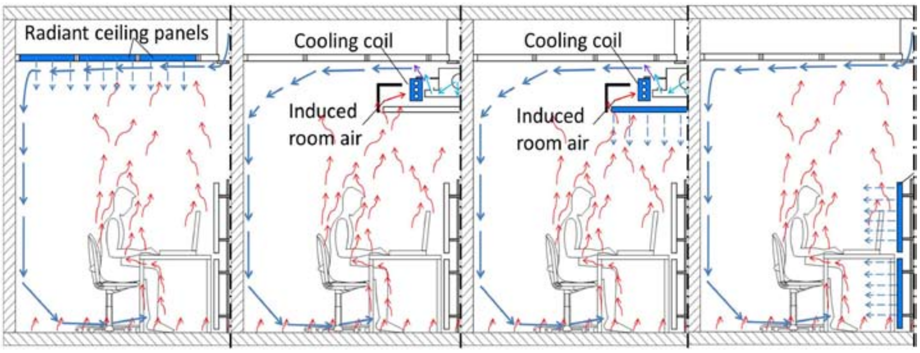

Figure 1. Operating principle of the four cooling systems (from left): radiant ceiling (CCMV), chilled beam (CB), chilled beam with radiant panel (CBR) and mounted local radiant cooling panels with mixing ventilation MVRC. Note: Only half of the room is shown with symmetry line on right side.

versus convection 50%). With chilled beam as with all-air systems, heat transfer is only based on convection.

It is commonly assumed that radiant cooling system has a significant influence on operative temperature. Some companies claim that operative temperature with radiant cooling is even 2 K lower than the room air temperature. However physical measurements performed in the occupied zone of a room showed no significant differences in thermal environment between radiant and convective cooling systems (Mustakallio et al. 2013). The difference in the operative temperatures was only 0.2 K between the two systems. Human perception of a room thermal environment obtained with radiant and convective cooling systems was also studied (Bolashikov et al. 2013). Whole body thermal sensation (TS) and whole body TS acceptability were at about the same level for the convective and radiant systems. Thus, there was not found any significant difference between the systems with regard to human response.

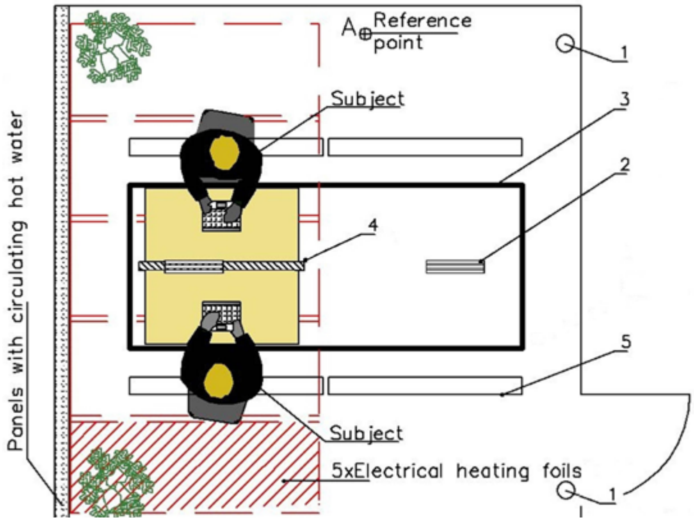

Figure 2. A) Top view of the test room with measurement pole locations: 1) ventilation exhaust, 2) ventilation supply, 3) chilled beam (CB), 4) desk partition mounted radiant cooling panels, 5) light fixtures, B) photograph of the measurement setup in CB, CBR and CCMV cases and C) photograph of the measurement setup in MVRC case (thermal mannequins above were used in actual measurements).

Comparison of radiant and convective cooling systems

The physical environment and human response to four air conditioning systems was studied. The systems comprised: chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with overhead mixing ventilation (CCMV) and four desk partition mounted local radiant cooling panels with overhead mixing ventilation (MVRC), **Figure 1**. Radiant ceiling was Uponor Comfort panel system integrated into the false ceiling tiles. Radiant ceiling covered maximum 77% of the total ceiling surface. The top surface of the tiles was not insulated. Supply air was discharged by two Halton SLN-472 linear diffusers. Halton CBR-2700-2100 chilled beam was used in both CBR case and CB case. For the CB case study there was no water circulation in the face panels of the chilled beam. Radiant panel surface area in chilled beam was 3.6 m². Chilled beam was removed from the ceiling when chilled ceiling cases were measured. The local radiant cooling (MVRC) was used during the experiments with people. Rettig panel radiators, PURMO Hygiene H10, were used to provide local radiant cooling. Supply air volume flow was increased under the MVRC cases in order to compensate for the reduced cooling power from the panel radiators.

Steady state conditions at 26°C air temperature were maintained in a test room (4.12 x 4.20 x 2.89 m, L x W x H) used to simulate the two persons office. Measurements at two heat loads, 64 W/m² (design conditions) and 38 W/m² (usual conditions) were performed. The heat load was generated from two occupants, computers, lighting units, and solar heat gains from windows and sun-lit floor just below the windows (**Figure 2**). Supply air temperature in all cases was kept at 16°C and water inlet temperature at 15°C with return water 2–3 K warmer.

Physical environment

Room air temperature, operative temperature, velocity and turbulent intensity were measured and draft rate levels calculated at 8 heights in the room for a grid of 25 points positioned within the occupied zone of the room. Surface temperatures and radiant temperature asymmetry were measured as well.

Average values of indoor climate parameters from the physical measurements are presented in **Table 1**. Average room air velocities were similar under all four systems. Top five highest velocities were within the range of 0.20–0.25 m/s. Those air velocity values are still in the acceptable range level.

Average room air temperature and operative temperatures were nearly the same with all four tested cooling systems. Average operative temperature was only 0.2 K cooler for the chilled ceiling (CCMV) than for the chilled beam (CB). This difference was close to the accuracy of the sensors. It should be noted that in all cases the average operative temperature was slightly higher than the room air temperature.

The reasons for small difference among the four systems are: 1) the temperature level of radiant surface is relatively high and 2) air distribution and convection flows of heat gains churn the room space. Specially, the effect of convection flow is remarkable with all systems. This is seen in the horizontal room air temperature gradient: there was quite significant temperature difference between window side and door side of the room (in design conditions 1.0–1.2 K and in usual case up to 0.7 K). However, the vertical temperature gradient was small with all system.

Human perception on thermal conditions

The response of twenty-four subjects, 12 males and 12 females all healthy and non-smokers to the thermal environment generated by the four cooling systems was collected during one hour exposure. The exposures to the four systems were randomized. The subjects were not informed which of the systems was in operation. The subjects reported on the whole body and local thermal sensation using ASHRAE's 7-point thermal sensation scale: cold, cool, slightly cool, neutral, slightly warm, warm and hot ASHRAE 55 (2010). EN 15251-2007. The acceptability of the thermal sensation experienced was reported on acceptability scale, from "clearly unacceptable" to "just unacceptable" and from "just acceptable" to "clearly acceptable" (EN 15251-2007).

Under the studied conditions, all four systems showed similar performance with respect to the whole body TS: occupants felt between "neutral" to "slightly warm" on the TS scale in EN 15251-2007. Female felt the 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 closer to "clearly acceptable" (EN 15251-2007) and was independent of the subject's gender for all tested systems.

Figure 3a compares the medians for each of the four experiments with CB, CBR, CCMV and MVRC systems. As can be seen no major difference were docu-

Table 1. 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

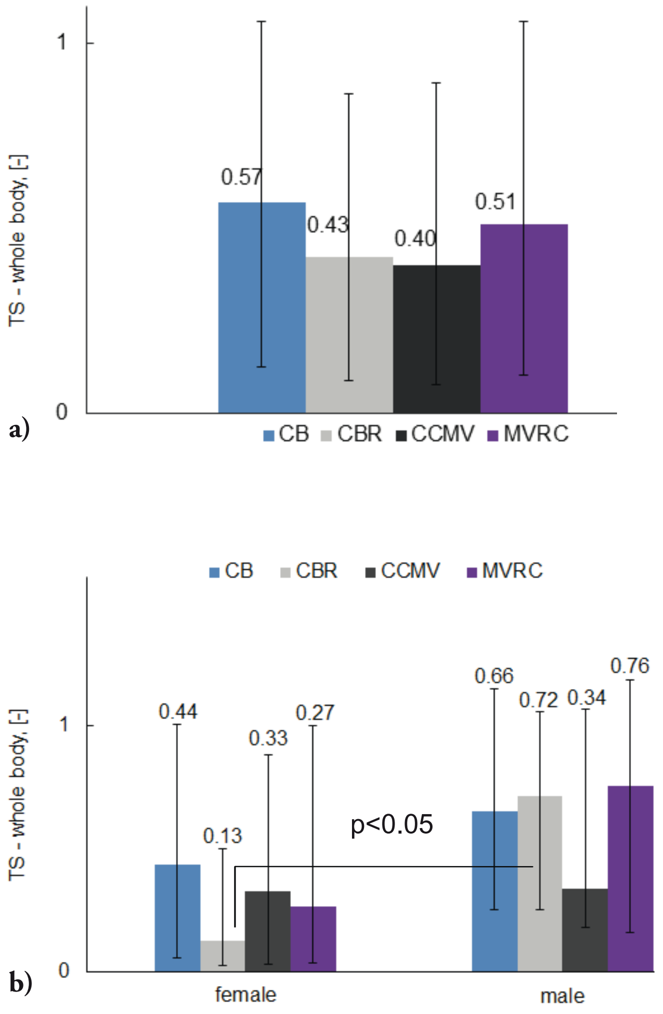

Figure 3. Whole body thermal sensation with the studied systems, CB, CBR, CCMV and MVRC; a) median of the whole body TS over the whole exposure, b) median of the whole body TS over the whole exposure divided by gender.

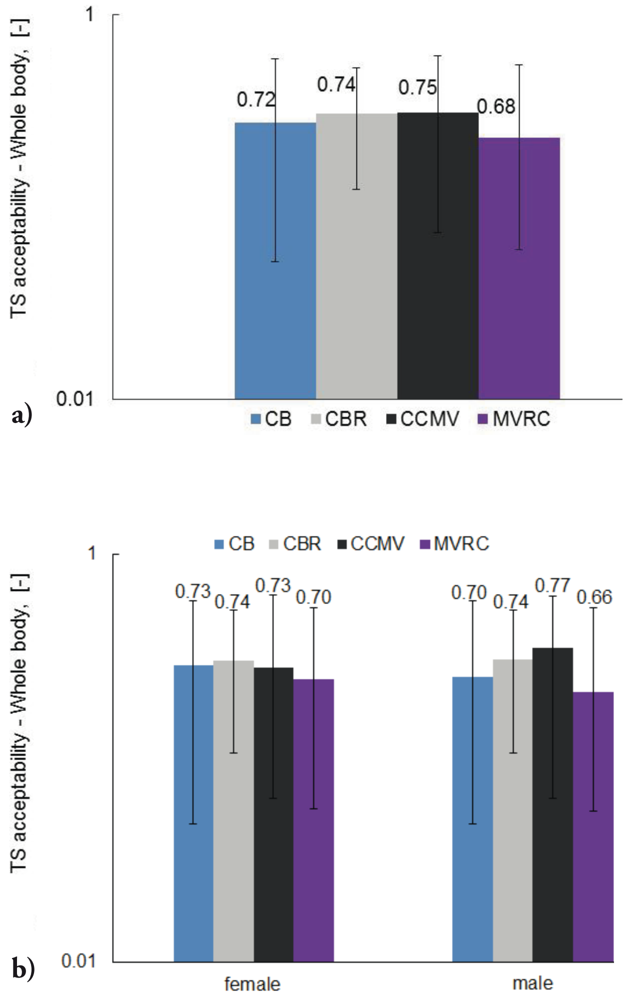

Figure 4. Acceptability of whole body thermal sensation with the studied systems, CB, CBR, CCMV and MVRC; a) median of whole body TS acceptability over the whole exposure, b) median of the whole body TS acceptability over the whole exposure divided by gender.

mented among the four systems tested. All of them managed to keep the thermal sensation of the subjects between "neutral" = 0 and "slightly warm" = 1.

Figure 3b is similar to **Figure 3a**, but here the median vote for the whole body thermal sensation are plotted as a function of the occupants' 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. Female subjects were significantly more sensitive to the whole body cooling with CBR than males.

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 4**. No clear difference could be observed among the systems based on the acceptability of the whole body thermal sensation felt.

Both females and males rated highly the acceptability of their whole body thermal sensation: the median vote was close to "clearly acceptable" = 1for all four systems. No clear trend in rating the systems based on whole body TS acceptability was documented for the female participants.

Conclusions

- The results revealed that the differences in thermal conditions between the convective and radiant systems were not big.
- An important finding was that air temperature and operative temperature were similar with convective or combined convective and radiant systems. This result was contrary to the expectation that operative temperature would be lower with radiant ceiling and local radiant cooling panel system
- Whole body thermal sensation acceptability was close to “clearly acceptable” with all tested systems.
- Female subjects were more sensitive to the provided cooling than male subjects. ■

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