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HUMAN PERCEPTION OF INDOOR ENVIRONMENT GENERATED BY CHILLED CEILING COMBINED WITH MIXING VENTILATION OR LOCALISED CHILLED BEAM UNDER COOLING MODE

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Abstract

Experiments with 24 subjects were performed to study and compare the human perception of the indoor environment under summer conditions generated by a chilled ceiling combined with overhead mixing ventilation and localised chilled beam. The experiments were performed in an experimental chamber (4.2 m x 5.4 m x 3.1 m) equipped as an office with two workstations. One of the workstations (with a laptop) was by the window and the other in the opposite side of the room. Five heated radiant water panels were used to simulate direct solar gains from windows (404 W). Five electrical foils were used to simulate direct solar load on the floor (270 W). The total heat load in the room was 56 W/m^2. The air temperature around the workstation by the window was kept either 26 or 28 ^{o}C. The supplied air by the overhead mixing ventilation and the primary supply air of the localised chilled beam was kept at 13 L/s and 16 ^{0}C. The localised chilled beam was installed over the workstation placed by the simulated window. During the experiment the subjects were delegated control over the primary flow rate supplied by the localised chilled beam. The whole exposure lasted 2 hours with 30 min of acclimatisation before the experiment. Every person spent in total 90 minutes at the workstation by the windows (three sets of 30 min), 10 min at the other workstation and 20 min away from the workstations performing office work at increased activity (1.4 Met). The primary airflow rate supplied by the chilled beam was reduced to 6 L/s during the 20 min period of physical activity, when the occupant was not at the desk with the localised chilled beam, resulting in increase of the air temperature in the room. Subjects used questionnaires to answer on thermal sensation and acceptability, perceived air quality, air movement and SBS symptoms. Under 26 ^{o}C the localised chilled beam provided more local cooling compared to the chilled ceiling. The opposite trend between the two systems was noticed at 28 ^{o}C. However the local thermal acceptability votes were similar for the two systems. Majority of the occupants did not wish change in the air movement at WS1 at 26 ^{o}C. With the chilled ceiling more subjects complained of not sufficient air movement especially at 28 ^{o}C. Most of the subjects tended to use the localised chilled beam at the maximum flow rate available, i.e. 13 L/s.

Keywords: localized chilled beam, chilled ceiling, user control, localised thermal comfort, air movement acceptability

1 Introduction

Energy saving directives have been introduced in many countries. It becomes challenging for designers and engineers to provide thermally comfortable indoor environment as recommended in the present standards ISO 7730 (2005) and EN 15251 (2007) at reduced energy consumption. Often air is used to provide clean air for breathing as well as to maintain temperature and relative humidity in the comfortable ranges. Substantial amount energy is used to condition and transport the air. 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 conditioned with such systems have been documented by physical measurements (Koskela et al. 2011, Kosonen et al. 2011, Duszyk et al. 2011 and Mustakallio et al. 2014). The results show that the generated indoor conditions result in strongly non homogeneous thermal environment. However human thermal perception to such non-uniform environment has been studied only little (Melikov et al. 2007) and requires further investigation. In indoor environments conditioned with such systems humans do not have control over the thermal environment. Research shows that heat plums generated within the occupied zone can push away the cool air provided by the chilled beam or mixing ventilation resulting in reduced local thermal comfort and reduced air movement (Koskela et al. 2011 and Mustakallio et al. 2014). Clearly new approach when using radiant and convective cooling is needed. Uth et al. (2014) studied a new concept for chilled beam application named localized chilled beam (LCB). An active chilled beam unit is installed in the ceiling above each workstation. The occupant seated below the LCB has the opportunity to control the supplied primary air within a certain range defined in the standards (EN 15251 2007). This novel approach of localised cooling can compensate for the thermal non-homogeneity of the generated environment, i.e. sun heated windows, proximity to hot surfaces etc.

The present paper reports on experiments performed with 24 human subjects in realistically simulated office room with two cooling systems under summer conditions: localised chilled beam (LCB) and chilled ceiling with overhead mixing ventilation (CCMV). Overall thermal sensation, its acceptability and perceived air quality have already been reported by Uth et al. (2014). The present paper reports on local thermal sensation and the amount of primary air from the LCB as individually controlled by the subjects. Detail physical measurements were performed as well but these are not subject of the current paper.

2 Method

A test room 4.12 m x 4.21 m x 2.89 m (L x W x H) was furnished as a single office with three workstations (WS) and a laptop (Figure 1). Heated radiant panels were used to simulate solar heat gain through the windows (404 W). Five electrical heated foils installed in half the floor area on the side of the windows simulated direct solar gain on floor. The total internal heat load in the room was 56 W/m^2. The main workstation (WS1) was placed near the simulated window (0.65 m away). It had a laptop (60 W). The location of the remaining two workstations was on the opposite side of the room, Figure 1. WS2 consisted of a bookshelf and was used to simulate typical transient activity in office environment (sorting books). WS 3 was opposite to the simulated windows, Figure 1. There the occupants performed either Sudoku game or solved crosswords.

The room air temperature around WS1 was kept at either 26 °C or 28 °C. The room indoor environment was generated either by LCB installed above the main workstation, or by a chilled ceiling combined with mixing ventilation (CCMV) with two ceiling slot diffusers located as indicated in Figure 1. Two exhaust diffusers were placed in the two corners of the room opposite to the simulated window, Figure 1. The air supplied by the mixing ventilation or the maximum primary air flow from the LCB was kept at 13 L/s and 16 °C. User control of the amount of primary airflow rate supplied from the LCB was introduced: from 6 L/s to 13 L/s.

The perception of the environment generated by the LCB and the CCMV was reported by 24 human subjects (12 male and 12 female) during four experiments (at two room temperatures with each of the two systems). During 2 hour-exposures preceded by 30 minutes of acclimatisation the subjects reported on their thermal comfort, perceived air quality, air movement sensation, sick building syndrome symptoms when performing computerised tasks under the micro-environment generated at WS1, when performing tasks at a WS3 and when performing office work at high activity level (sorting magazines) at WS2. This gives in total three exposures at WS 1, one at WS 3 and one at WS

2. The experimental procedure and the time when subjects reported on different questions are shown in Figure 2. An energy saving strategy by decrease in supplied air flow to 6 L/s from the LCB was introduced during the high activity work task at WS2. This resulted in increased room air temperature.

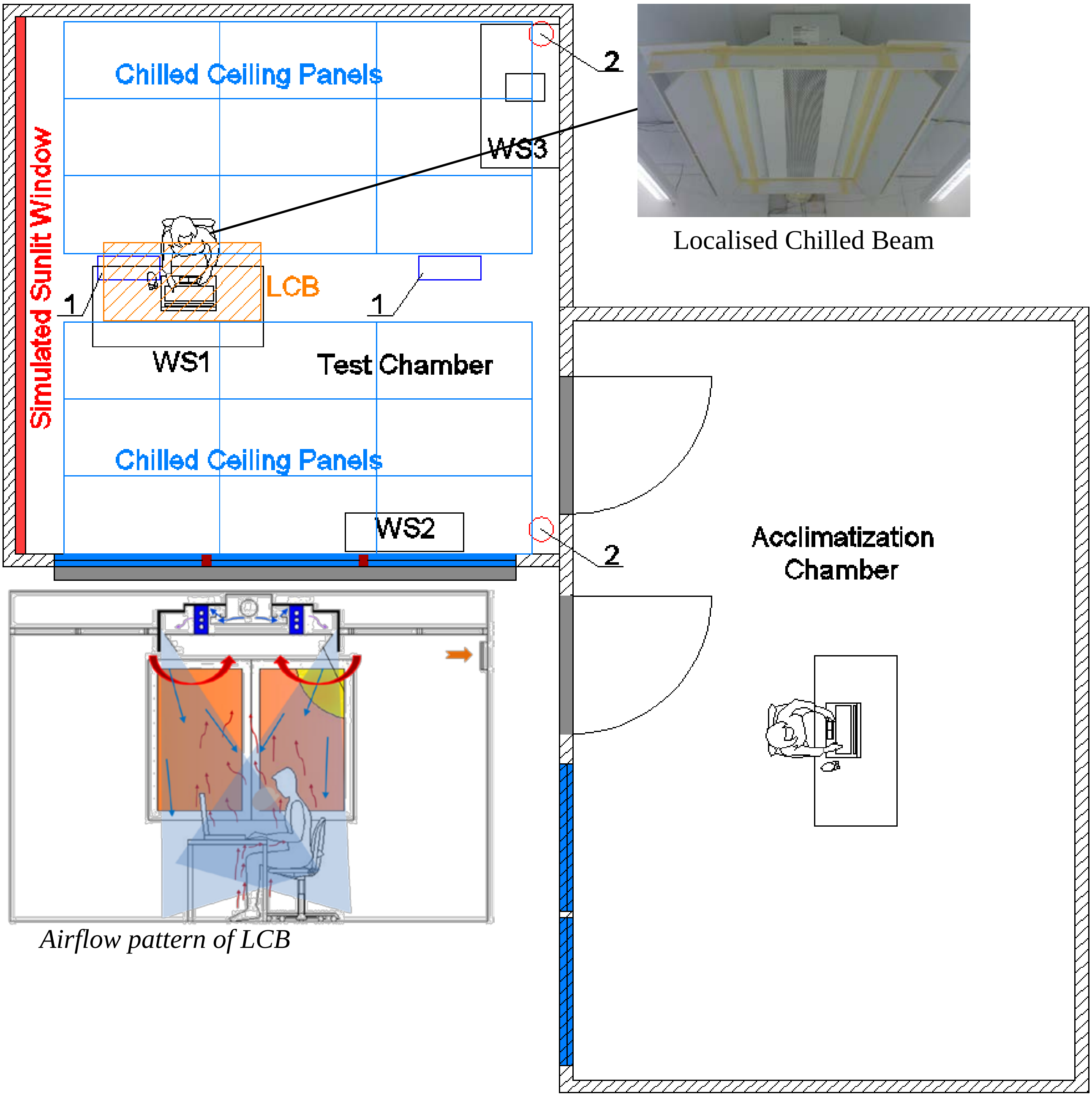


Figure 1. Experimental chamber: 1) mixing supply air ceiling diffusers; 2) ceiling mounted exhaust; LCB –local chilled beam; WS -workstations

Questionnaire schedule	Acclimation	Entry	Worksession 1 (WS1)	Paper tasks (WS3)	Worksession 2 (WS1)	High activity (WS2)	Worksession 4 (WS1)
PAQ	X X	X	X X	X X	X X	X X	X X
OTS	X		X X	X X	X X	X X	X X
LTS			X	X	X	X	X
IEQ	X		X	X	X	X	X
SBS	X		X	X	X	X	X
Clothing			X	X	X	X	X
Tearfilm	X						X
Blinking							
Skin temp							
Comments							X
Miscellaneous	X						
Time [min]	15 15		15 15	10	15 15	10 10	15 15
Chamber	Chamber 6	Chamber 5		Chamber 5	Chamber 5	Chamber 5	Chamber 5

Figure 2. Procedure of the experiment

The subjects evaluated how they felt the thermal environment - overall thermal sensation (OTS) and local thermal sensation (LTS) on ASHRAE’s 7-point scale (cold: -3, cool: -2, slightly cool: -1, neutral: 0, slightly warm: 1, warm: 2, hot: 3), whether they felt air movement and air movement preference (more, less or no change in air movement), air freshness on continuous scale (air stuffy – air fresh) and acceptability of thermal sensation and perceived air quality (PAQ) on a scale with two parts: continuous scale from clearly unacceptable (-1) to just unacceptable (-0.1) and then another continuous scale from just acceptable (0.01) to clearly acceptable (1). The questions related to SBS symptoms and indoor environmental quality in general were based on a continuous scale (0-100).

Physical measurements were performed following the human subject experiment. A thermal manikin of complex body shape and geometry was used to simulate the human occupant. Air speed, air and operative temperature and radiant asymmetry were measured in order to identify the indoor environment and to compare with human subject response. A grid of 24 measuring points was used to perform the physical measurements. Further, the supplied air flow from the LCB was visualised by inducing smoke into the inlet air duct. Air speed and temperatures were measured at eight heights (0.05, 0.1, 0.3, 0.6, 1.1, 1.4, 1.7 and 2.0 m) in each point from the grid for an average of a 5-minute period. However the results of these measurements are not reported in this paper.

The data obtained from the human subject experiments were statistically analysed. The data was first tested for normality distribution by using the Shapiro-Wilcoxon test. The test threshold level of $p< 0.05$ was chosen. If the test resulted in a p-value lower than 0.05 the data were not normally distributed, however, if it was higher than 0.05 the data is assumed to be normally distributed. In the cases where the data was not normally distributed analysis was done with the non-parametric Wilcoxon matched pairs test. Significance level $p\leq 0.05$ rejected the null (H0) hypothesis that the results were similar, i.e. the possibility of a considerable difference in result data. For the data showing normal distribution, i.e. the Shapiro-Wilcoxon test with $p > 0.05$, repeated measure analysis of variance (ANOVA) was performed, with the Newman-Keuls, Post-hoc test method. p-values below 0.05 are marked with “*”on figures.

3 Results and Discussion

3.1 Local Thermal Sensation and Local Thermal Sensation Acceptability

Uth et al. (2014) showed that there was no significant difference in the self-reported whole body thermal perception and its acceptability by the participants between the two systems tested: localized chilled beam (LCB) and chilled ceiling with mixing ventilation (CCMV). However at the 26 ^{o}C background room temperature LCB performed slightly better than CCMV. The results presented in this paper concentrate on the local thermal sensation at WS 1 and the use of individual control with the LCB system.

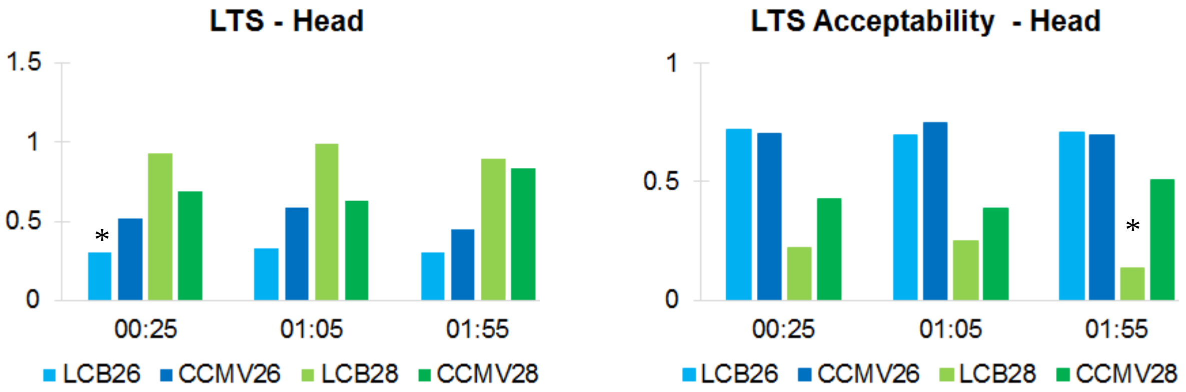
The local thermal sensation (LTS) for selected body parts (exposed upper body parts) and acceptability (median) for the 24 subjects are shown in Figure 3. Under 26 °C the localised chilled beam provided the same or more cooling locally compared to the chilled ceiling combined with overhead mixing ventilation. However no differences in the LTC acceptability were noticed between the two systems. Under 28 °C the opposite trend was observed, Figure 3. LCB provided significantly less cooling compared to CCMV, which also lead to the lower thermal acceptability of the LCB system compared to the CCMV. The LTS votes were very close to each other, Figure 3. However, the LTS acceptability votes under the LCB system were significantly lower during the third exposure at workstation 1 compared to CCMV, Figure 3. This was due to the fact that the occupants came after performing physical activity at workstation 2. In the case of CCMV the background temperature was slightly lower than at the reference point: the latter being close to the simulated windows and within the air flow of the LCB. However, the cooling performance of LCB surpassed that of the CCMV for the exposed upper body parts, since the air flow pattern was more direct and had higher air velocities (based on physical measurements not reported here).

The other body parts that were included in the questionnaire are not shown, as there was no noticeable difference between the two systems' performance with respect to LTS and LTS acceptability under the two tested temperature conditions of 26 and 28 ^{o}C.

As subjects had the possibility to change the air flow rate during the experimental conditions with the LCB, the cooling amount for the two systems (LCB and CCMV) was different. A calculation of the output cooling power of the two systems showed, that the CCMV had a higher total output of cooling power, Table 1. This in fact can explain the higher acceptability of the LTS with CCMV under 28 ^{o}C compared to the LCB system. The applied strategy of energy saving by reducing the flow rate of air supplied from the LCB when the subject was not present led to decrease thermal comfort.

Table 1*: Comparison of cooling power of the two systems LCB and CCMV*

Total cooling power				
	LCB	*CCMV*		
	Qair [W]	*Qair [W]*	*Qceiling [W]*	
26 °C	597	131	690	$\Delta Q = Q_{CCMV} - Q_{LCB}$ [W]
28 °C	511	157	460	
Total 26 °C	597	821		**224**
Total 28 °C	511	617		**106**



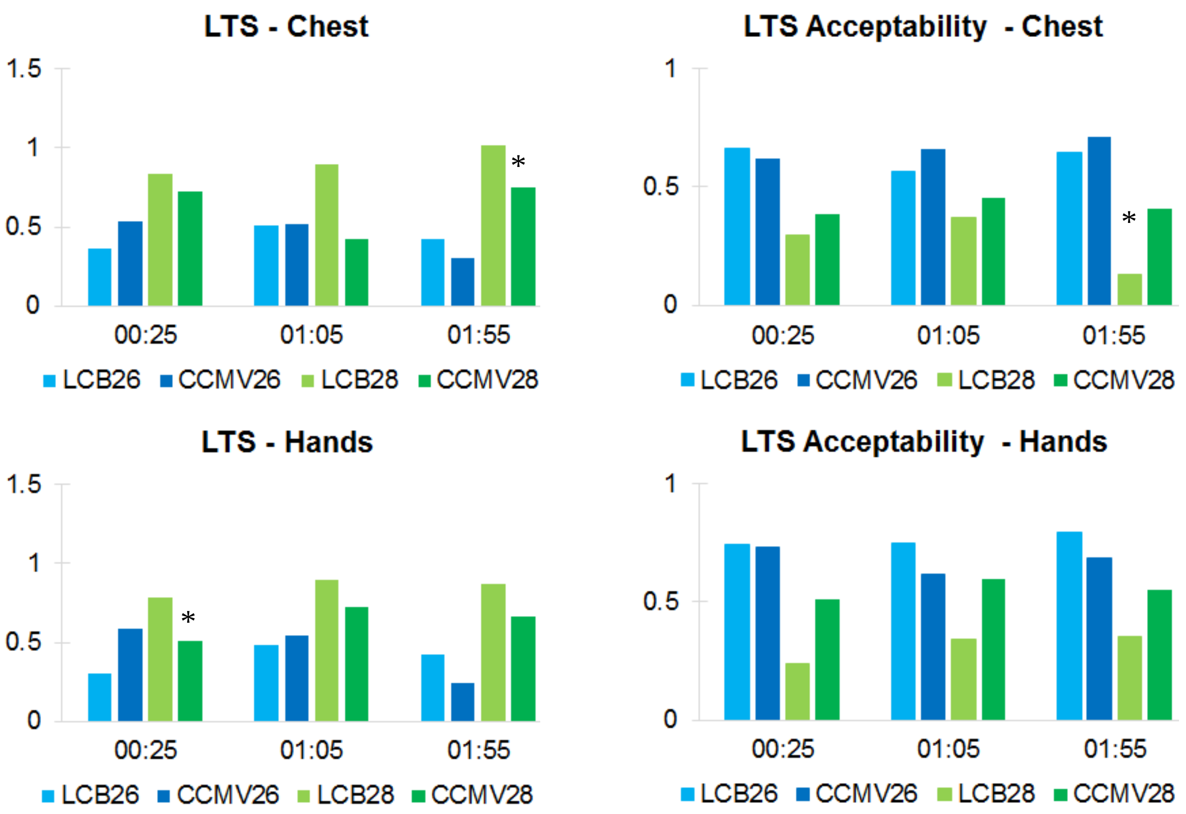


Figure 3. LTS and LTS acceptability for a) top of head, b) chest and c) hands. The thermal sensation scale is: -3 – "Cold", -2 – "Cool", -1 - "Slightly cool", 0 - "Neutral", 1 - "Slightly warm", 2 - "Warm", 3 –" Hot". The thermal acceptability scale is: -1 – "Clearly unacceptable", -0.01 – "Just unacceptable", 0.01 – "Just acceptable", 1 – "Clearly acceptable" according to EN 15251 (2007).

3.2 Primary air flow control for the LCB unit

Table 2 shows the median primary air flow, minimum and maximum as well as 25 and 75 % quartiles for all subjects for the LCB under the two room air temperature tested during the whole exposure of two hours.

***Table 2:** Median, min and max and 25/75 % quartiles for air flow settings for all subjects during the exposure*

Condition	*Median [L/s]*	*Min [L/s]*	*Max [L/s]*	*25 % Quartile*	*75 % Quartile*
LCB26	13.2	6.3	13.3	6.5	13.2
LCB28	13.2	6.1	13.2	9.5	13.2

***Table 3**: Subjects expressing a wish for more air movement, while not having a high air flow setting at the end of the exposure*

Air movement preference vs vote				
Condition	*LCB26*	*LCB26*	*LCB28*	*LCB28*
Subject #	19	42	28	6
Air flow setting [L/s]	6.4	6.5	10.2	6.4
Vote	M+	M+	M-	M-

Four subjects expressed a wish for more air movement at the end of the exposure with LCB, Table 3. However, it was observed from the data that those subjects were not taking advantage of the possibility to control the primary airflow of the LCB. The four mentioned subjects voted for more air (M stands for more) and the sensing of air movement around the person with + or -. The "+" stands for the subject being aware of the air movement and the "-" sign that he/she was not feeling any air movement at all.

The percentage of subjects who wanted more air movement is shown in Table 4. Clearly subjects did not use enough the provided control over the primary air flow. 43 % of the subjects who voted for more air had lower than the max primary flow for LCB26. Elevating the background room temperature seemed to stimulate the subjects to better exercise the delegated control: only 16 % voted for more, while not having set the maximum air flow.

Table 4*: Air movement preference and setting (entire exposure)*

Condition	*LCB26*	*LCB28*
Percentage that wanted more with 13 L/s	57	84
Percentage that wanted more air with <13 L/s	43	16

3.3 Air movement

Subjective response to air movement during the whole exposure when situated at the different work stations showed that the air movement in general was found acceptable for both 26 °C and 28 °C conditions. For the condition with 26 °C the majority of the occupants were satisfied with the air movement at WS1 for both systems. At 28 °C there was a higher demand for more air, Figure 4. Also the number of subjects who demanded more air and found the present level acceptable was equal to those who demanded more air but found the air movement unacceptable for both of the tested systems.

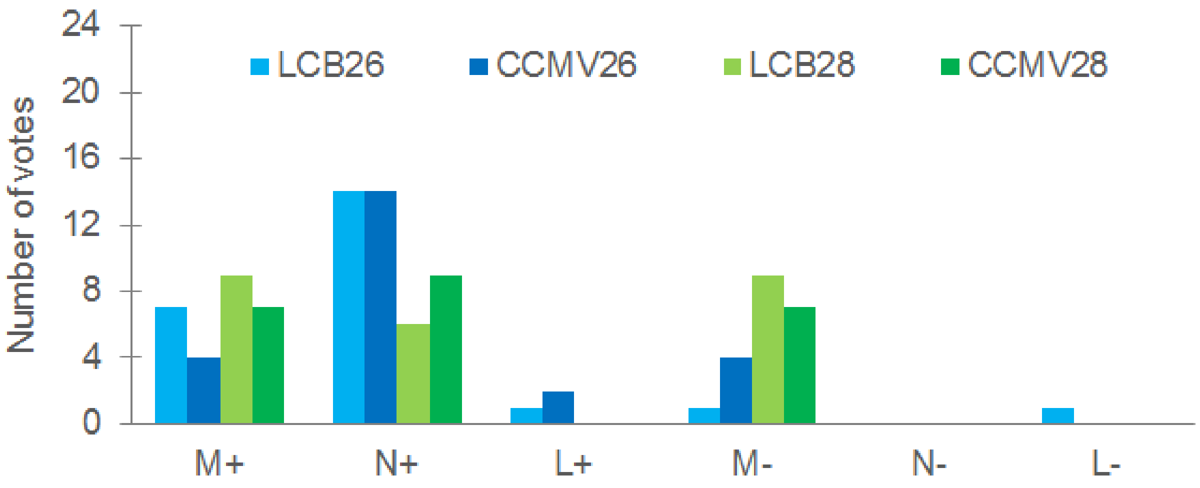


Figure 4. Preferred air movement at WS1 at the end of the exposure. M – More air, N – No change, L – Less air, + acceptable, - unacceptable

From performed visualisations became clear that the air flow from the LCB glided behind the seated occupant forming a dome around him. This in fact explains the need of more air movement requested by many subjects. More direct flow towards the occupant is a possible solution. However the change could result in draught, as the occupant would be more exposed suggesting further optimisation of the LCB design.

4 Conclusion

- No significant difference in local thermal sensation and local thermal sensation acceptability between LCB and CCMV was reported by the subjects. LCB provided slightly more cooling to the upper body under 26 °C compared to CCMV. At 28 °C the opposite tendency was observed.

- The majority of the occupants did not wish for any change in air movement at WS1 at 26 °C under both systems. Subjects wished for more air at WS1 under the condition with 28 °C for both systems.
- In the present study the subjects did not exercise the delegated primary air flow control of LCB as much as expected. Even the elevated room air temperature was not stimulating incentive to improve the control use of the primary air supply of the LCB.

5 Acknowledgement

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