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Topic B3: Control of indoor environment

HUMAN RESPONSE TO INDIVIDUALLY CONTROLLED MICRO ENVIRONMENT GENERATED WITH LOCALIZED CHILLED BEAM

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SUMMARY

Indoor environment in a single-office room created by a localised chilled beam with individual control of the primary air flow was studied. Response of 24 human subjects when exposed to the environment generated by the chilled beam was collected via questionnaires under a 2-hour exposure including different work tasks at three locations in the room. Response of the subjects to the environment generated with a chilled ceiling combined with mixing air distribution was used for comparison. The air temperature in the room was kept at 26 or 28 °C. Results show no significant difference in the overall and local thermal sensation reported by the subjects with the two systems. Both systems were equally acceptable. At 26°C the individual control of the localised chilled beam lead to higher acceptability of the work environment. At 28°C the acceptability decreased with the two systems. It was not acceptable with the localized chilled beam.

INTRODUCTION

At present, uniform indoor environment is mainly used in buildings design, i.e. uniform temperature and velocity field in the occupied zone. However, large differences exist between people with regards to the preferred indoor environment. Activity level of occupants also changes during the day. The used at present total volume air conditioning systems are not able to provide each occupant with preferred environment.

Energy saving is an important consideration in buildings design, operation and maintenance. Indoor environmental systems consume substantial part of the energy used in the building sector. Use of combined convective and radiant heat exchange is used to reduce energy. Chilled ceiling combined with mixing ventilation is a typical example. It is claimed by the manufacturers that such systems also improve occupants' thermal comfort at warm environment, since the generated operative temperature is lower than the air temperature in the conditioned space. However these systems still have the disadvantages of all total volume air-conditioning systems, namely that occupants have limited or no control over the generated environment.

Flexibility in space use is an important requirement in many buildings. Change of tenants leads to change in layout in rooms and change in the space use. It is well known that indoor environment in rooms is strongly dependant on the interaction of ventilation, buoyancy and other flows. Changes in the room layout most often lead to changes in locations and strength of heat sources. Thus airflow interaction changes and is not possible (or very difficult) to control the airflow pattern and the environment in rooms with total volume air conditioning systems in general.

An innovative design of chilled beam, named localized chilled beam (LCB), generating individually controlled micro-environment at an office workstation, has been suggested. Human subjects' response to the non-uniform room environment generated with the LCB design was studied and reported in this paper. Subjective response was compared with that to the environment generated with chilled ceiling combined with mixing ventilation.

METHODS

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 and a laptop (Figure 1). Heated radiant panels were used to simulate solar heat gain through the windows. 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/m². The main workstation (WS1) was placed near the simulated window (0.65 m away). 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.

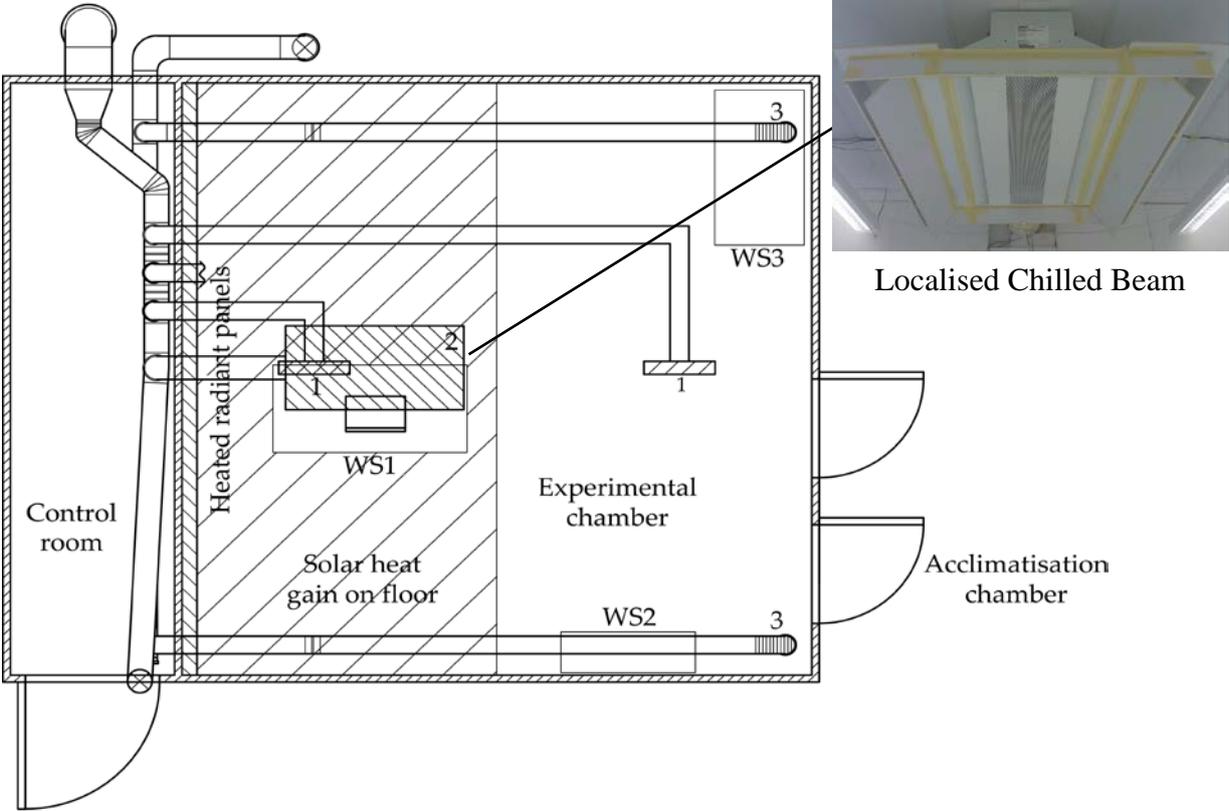


Figure 1. Experimental chamber, 1) mixing supply air ceiling diffusers, 2) localised chilled beam, 3) ceiling mounted exhaust

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 with two ceiling slot diffusers (CCMV). 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 primary airflow rate supplied from the LCB was introduced.

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. The experimental procedure and the time when subjects reported on different questions are shown in Figure 2. A decrease in supplied air flow to 6 L/s was introduced during the high activity work task at WS2 for the LCB system.

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
OTS		X	X	X X	X X	X X	X X
LTS				X	X	X	X
IEQ		X		X	X	X	X
SBS		X		X	X	X	X
Clothing				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 feel 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 continuous scale from clearly unacceptable (-1) to just unacceptable (-0.1) and then 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).

Based on the overall thermal sensation acceptability ratings of the subjects, percentage of dissatisfied subjects (PD) when situated at WS1 was calculated by the following equation:

$$PD = \left(\frac{\exp(-0.18 - 5.28 * \overline{ACC})}{1 + \exp(-0.18 - 5.28 * \overline{ACC})} \right) * 100$$

where \overline{ACC} is median vote of acceptability at WS1.

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 (H_0) 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 < 0.05 are symbolised on figures as “*”.

RESULTS AND DISCUSSION

The environment generated in the room by the CCMV was not uniform. The buoyancy flow generated by the simulated window with high surface temperature pushed the air supplied by the ceiling mounted slot diffusers to the opposite side of the room. The airflow supplied by the LCB was less affected by the buoyancy flow from the windows. Subjects used the provided control of the primary air flow rate supplied from the LCB to achieve preferred environment while working at WS1 as well as to improve their thermal comfort when they moved back to WS1 from the warmer background environment where their activity was higher.

The performance of the two systems was similar with individual strengths and weaknesses. A highly non-uniform room environment was created by the LCB, with background temperatures up to 2 K higher than the set room temperature (physical measurements not reported here). However, statistical analysis of the results showed no significant difference in the votes between the two systems when the subjects were within the comfort zone of the LCB, i.e. when sitting at WS1. As subjects were away from WS1 outside the conditioned LCB work environment, the CCMV showed better results. With the LCB the air (and operative) temperature outside the LCB were higher. This resulted in elevated thermal sensation reported by the subjects.

From the votes of the overall thermal sensation (OTS) (Figure 3) it can be seen that the CCMV had a higher cooling effect than the LCB. 25 and 75 percentiles are also shown on the figures. OTS was generally voted higher, closer to slightly warm and even warm sensation for the LCB. For all the last votes at WS1 (time 00:25, 01:05, 01:55), no significant difference ($p < 0.05$, otherwise symbolised as an “*” in figures) was found between the two systems for both temperature conditions. Last votes of OTS show that a “steady-state” condition was reached when returning to WS1 after the increased activity involvement of the subjects (time 01:30). The experienced cooling effect of the LCB was significantly higher than the CCMV for this time-period, hence the much steeper slope of LCB26 than for CCMV26 in the time interval 01:25 to 01:55 (Figure 1). This was expected since more direct convective cooling occurs from the LCB. The same trend can be seen in the condition of 28 °C. The fact that the slope is steeper can also be explained with the higher experienced cooling effect at the higher temperature that is felt stronger compared to that at 26 °C, i.e. higher cooling effect was seen when subjects felt warm OTS compared to when they felt close to neutral. The decrease in primary air flow during high activity work at WS2 resulted in an increase in room air temperature, thus increasing the OTS for subjects significantly during (and a time period) after, where subjects again could control the air flow as wanted. The fact that the LCB was able to reach a steady state for OTS after 30 minutes (Figure 3) suggests a higher degree of acceptability for subjects exposed to a non-uniform environment when those have control over the primary air flow.

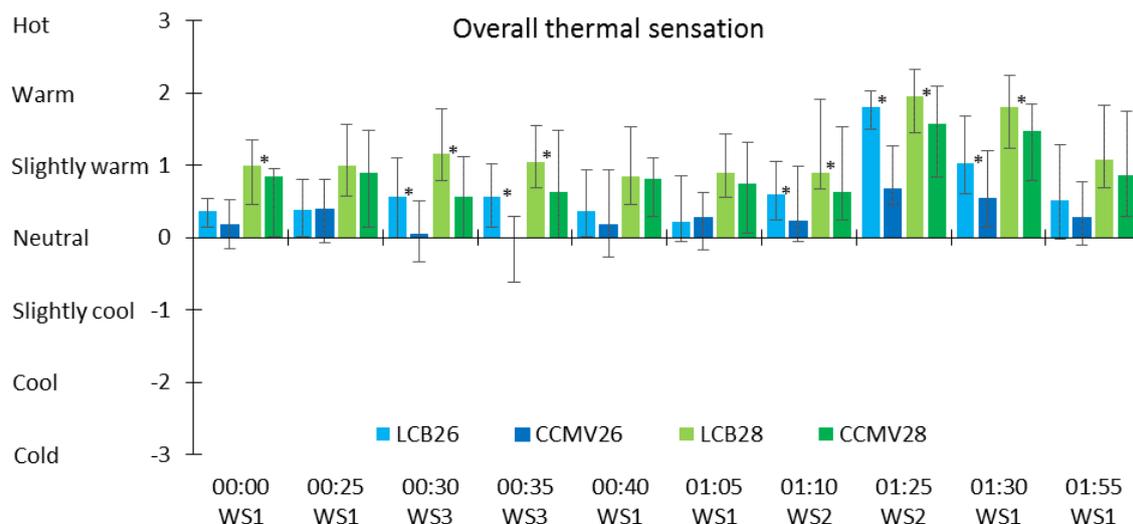


Figure 3. Median overall thermal sensation votes from subjects with 25 and 75 percentiles in time during the 2 hour exposure period. $p < 0.05$ is marked with *.

The overall thermal sensation acceptability votes are shown in Figure 4. The thermal sensation acceptability line over the exposure time is following the same trend for all four conditions. A clear drop in thermal sensation acceptability occurs throughout the transient activity at WS2. However, after being exposed for the last 30 minutes at WS1, the same acceptability level as with previous exposures at WS1 was reached, Figure 4. Same tendencies are seen for LCB28 and CCMV28.

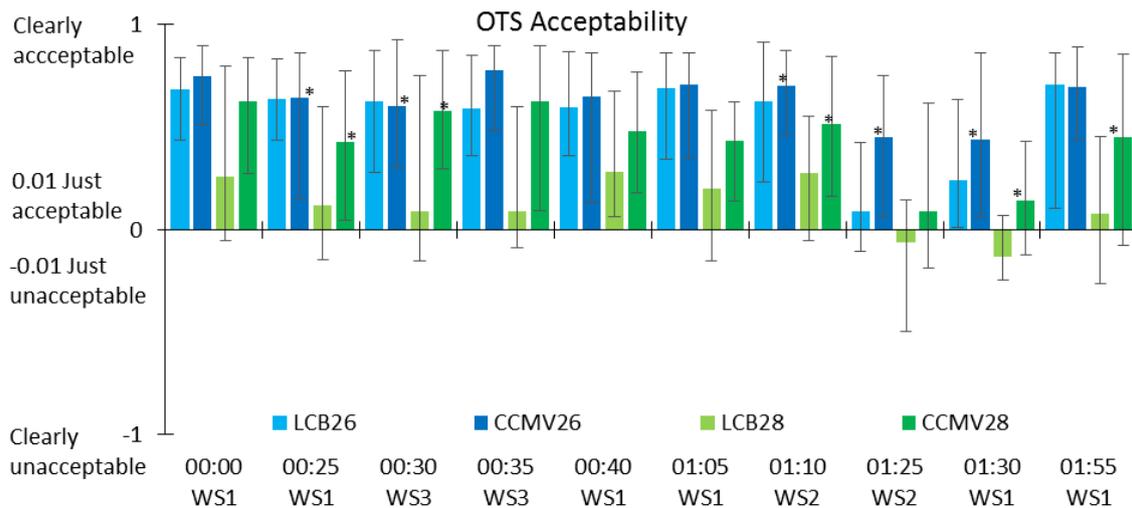


Figure 4. Median overall thermal sensation acceptability votes from subjects with 25 and 75 percentiles. $p < 0.05$ is marked with *.

The median values for perceived air quality are shown in Figure 5. As expected, the perceived air quality (PAQ) was higher when subjects were situated in the comfort zone of the LCB (WS1) than when at WS3 or WS2. The PAQ with LCB at 26 °C was more acceptable compared to CCMV under the same other conditions at WS1. However, throughout the exposure, PAQ was lower for LCB28 than for CCMV28. When subjects were outside of the LCB comfort zone, the PAQ was decreased. At the end of the transient activity at WS2 the PAQ was significantly lower for LCB26 than for CCMV26.

PAQ was generally lower for the 28 °C condition compared to the 26 °C condition. This can be explained by the effect of the elevated room temperature. The perception of air quality was affected by the air temperature (Fang et al. (1998); ASHRAE Guideline 10 (2011)) which explains the lower votes on air quality between the two temperature conditions. After the transient work session at WS2, PAQ with the LCB and the CCMV was voted the same for 28 °C and was voted lower for LCB at 26 °C (with $p < 0.05$).

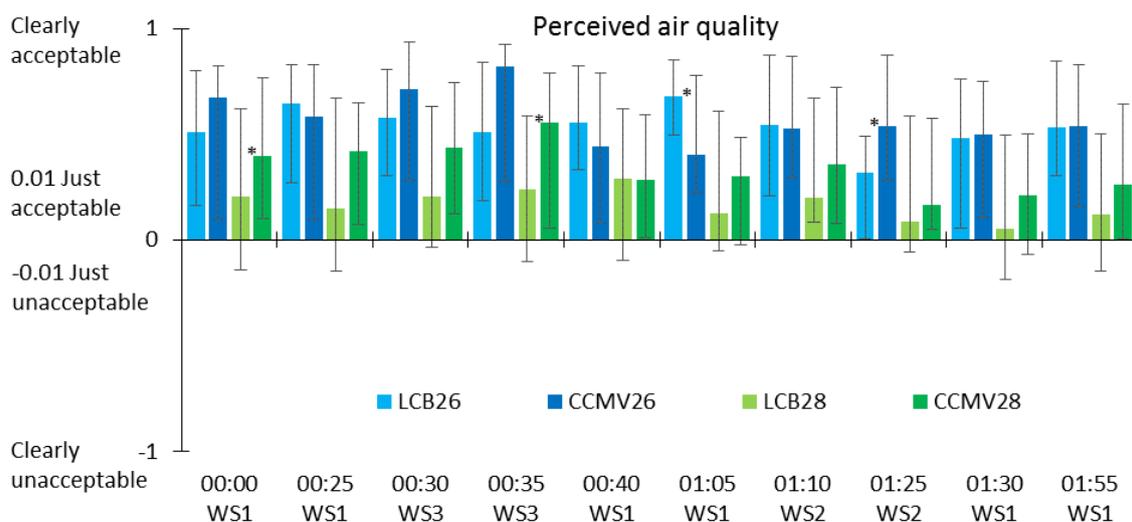


Figure 5. Median perceived air quality votes from subjects with 25/75 percentiles. $p < 0.05$ is marked with *.

The results for PD for OTS votes at WS1 are listed in Figure 6. The results show, that LCB26 and CCMV26 are both categorised as category I according to EN 15251 (2007). CCMV28 is categorised as Category II and LCB28 as Category IV (as PD exceeds category III). The PD for LCB28 being so high, can also be extracted from Figure 4, where OTS acceptability is voted relatively low compared to the other system and conditions.

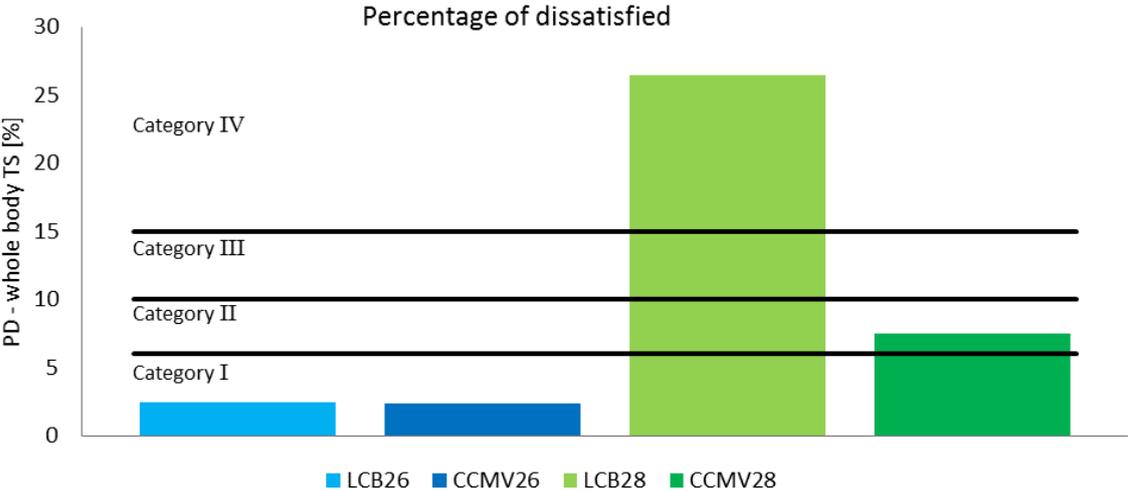


Figure 6. Percentage of dissatisfied calculated for the four systems from OTS votes at WS1.

Each subject was asked to evaluate the overall indoor environment acceptability, considering it their work place for 8 h per day 5 days a week. The highest voted system was the LCB under the 26 °C condition, however, with no significant difference compared to the conditions of the CCMV system ($p= 0.78$), Figure 7.

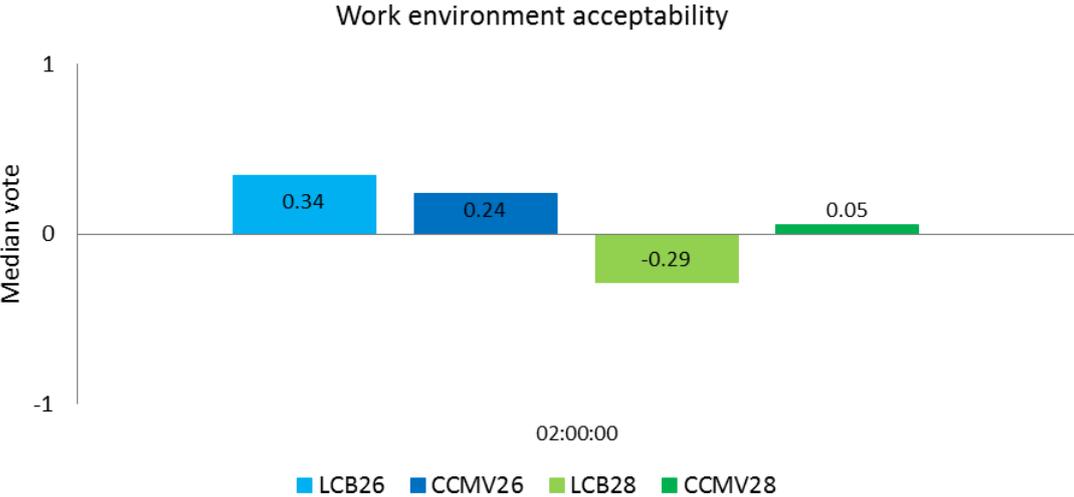


Figure 7. Median voted overall work environment acceptability.

Recent studies (Melikov & Kaczmarczyk 2012) revealed that elevated air movement counteracts the negative impact of increased air temperature and humidity on PAQ. Votes reported at the end of the session at WS3 showed that the PAQ was lower under the LCB than

under the CCMV with significant difference at 28 °C. This was expected, as the subjects were positioned outside the LCB ventilation zone. After returning to WS1 again, the subjects favoured the PAQ of the LCB. The same trend was observed at WS2. However, here significant difference in PAQ was seen when comparing the two systems for the 26 °C condition (Figure 4). The positive impact of air movement on PAQ reported by Melikov and Kaczmarczyk (2012) explains the results of the favouring of LCB, since elevated air movement was found near the occupant providing local cooling to the face and head. Under higher temperature conditions, PAQ was voted lower with same inlet air temperature and outdoor conditions used for all conditions. This suggests the perceived air quality was affected by air temperature, making the air feel stuffier. This result concurs with the negative impact of high temperature on PAQ reported by Fang et al. (1998).

CONCLUSIONS

No significant difference in whole body thermal sensation and local thermal sensation was reported by the subjects when exposed to the environment generated by localized chilled beam and chilled ceiling combined with mixing ventilation.

The individual control of the primary air flow of the LCB increased the user satisfaction. The direct flow from the LCB to the occupant increased the convective cooling to the upper “exposed” body parts (head, neck, arms and hands). The individual control of the primary air for LCB makes it possible to satisfy a wider range of occupants.

For all four conditions (LCB26, LCB28, CCMV26 and CCMV28) the perceived air quality (PAQ) was voted acceptable.

A stabilising period for overall thermal sensation was observed after the transient work session. Both systems were able to reach a “normalised” level (from before transient work) during the last 30 minutes of exposure.

ACKNOWLEDGEMENT

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