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HUMAN RESPONSE TO PERSONALIZED VENTILATION COMBINED WITH CHILLED CEILING

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Abstract

Personalized ventilation (PV) improves inhaled air quality, because it provides fresh air to each workstation and directly to occupant's breathing zone. Previous research was focused on combining PV with additional total volume air distribution, i.e. mixing ventilation or displacement ventilation, which was responsible for keeping the design air temperature conditions in the occupied zone. Removing room sensible heat load with radiant cooling systems enables reduction of required supply airflow rates which can make it possible to use the PV as a single ventilation system in the room. Furthermore, the use of radiant ceiling cooling will provide operative temperature lower than the air temperature and will improve further occupants' thermal comfort at warm environment. Therefore combining PV with chilled ceiling may be an effective way to provide thermal comfort in rooms at temperature higher than the recommended in the standards upper temperature limit of 26°C.

In this paper response of 24 human subjects to a PV combined with chilled ceiling system (CCPV) is compared with the response to mixing ventilation combined with chilled ceiling (CCMV). Participants were provided with control of direction and flow rate of the air supplied from the PV. Air quality and thermal comfort perceived by subjects were studied during 3-h. exposures. Room air temperature was kept at 26°C and 28°C. Supplied air temperature (by PV and mixing ventilation) was 3 K lower than room air temperature. Average supply/return water temperature for chilled ceiling was 15,5/16,8°C at room air temperature of 26°C and 19,5/20,6°C at 28°C. During the experiment the subjects were performing typical office tasks at workstations with computers. Exposure included also increased activity level office work for a period of 25 min.

At the workstation PV provided overall thermal sensation close to neutral, whereas thermal sensation above neutral was reported during the exposure with CCMV. In the room away from the workstations the thermal sensation and its' acceptability was similar with both systems. Immediately after the increased activity period subjects' thermal sensation ranged between warm and hot. After returning to the workstations the use of PV helped subjects to improve their thermal sensation much faster (5 min) compared to the CCMV (30 min). Air at workstation was perceived as more fresh with CCPV than with CCMV. Percentage of dissatisfied with air quality was lower in the cases with CCPV system compared to CCMV. Both studied systems created similar thermal and air quality conditions in the occupied zone outside of the workstations.

Keywords: radiant ceiling cooling, personalized ventilation, thermal comfort, perceived air quality

1 Introduction

Thermal environment and indoor air quality affect health, comfort and performance of office workers (Seppanen et al., 2002; Wyon and Wargocki, 2013). Thus creating comfortable conditions in spaces at low energy use becomes an important challenge for HVAC engineers. Centrally controlled ventilation systems, e.g. mixing or displacement ventilation, which are typically used in offices, create uniform indoor environment in the occupied zone of rooms which may not be preferred by all occupants.

The radiant chilled ceiling is a popular cooling solution as it removes greater part of sensible heat load from the room by radiation. Use of radiant cooling system enables to decrease the supply airflow rate required for room conditioning and is more energy-efficient than cooling by total volume ventilation systems. Chilled ceiling provides operative temperature lower than air temperature. Traditionally chilled ceiling is combined with mixing ventilation or displacement ventilation (Rees and Haves, 2013; Bahman et al. 2009). These systems supply fresh air far from occupants and before it reaches the occupants' breathing zone it is mixed with pollution in the room. Personalized ventilation (PV), in a contrary to mixing and displacement ventilation, supplies fresh air straight to occupant's breathing zone (Melikov, 2004). Therefore combination of chilled ceiling with personalized ventilation may be promising. The disadvantages of total volume air distribution methods (mixing and displacement) as well as advanced methods of room air distribution are discussed by Melikov (2011).

Physical measurements of the thermal environment and air quality conditions performed by Lipczynska et al. (2014a and 2014b) showed that PV when combined with chilled ceiling can be successfully applied as a single ventilation system. Combined system of chilled ceiling and personalized ventilation (CCPV) resulted in achieving similar indoor environment in the occupied zone as with chilled ceiling combined with mixing ventilation (CCMV), but PV created superior conditions at the workstations. Use of PV instead of mixing ventilation in combination with chilled ceiling substantially increased the inhaled air quality. Pollutants concentration in the inhaled air decreased up to 84% and the airborne cross-infection risk dropped up to 81% depending on the PV airflow rate.

This paper presents evaluation of the thermal conditions and perceived air quality of the environment created by the combined systems of CCPV or CCMV during human subjects' experiments.

2 Methodologies

Human response to the environment provided with chilled ceiling combined with personalized ventilation (CCPV) and chilled ceiling combined with mixing ventilation (CCMV) was studied in the climate chamber arranged as an office with two workstations. Room lay-out is presented in Figure 1. 24 human subjects (12 female and 12 male) participated in four 3-h. exposure sessions. The performance of the systems was studied at room air temperature of 26°C and 28°C. The order of four conditions (CCPV and CCMV at 26°C and 28°C) the subjects were exposed to was randomized. To become familiar with questionnaires and the experimental procedure, subjects took part in one training session before the experiments started.

PV used round movable panel (RMP, Bolashikov et al., 2003) as an air terminal device installed at each workstation (WS1 and WS2, Figure 1). The RMP was attached to a flexible arm allowing for change in its positioning. Linear diffusers mounted at the centre of the ceiling were used for mixing ventilation. The supply air flow rate of 26 L/s for ventilation was calculated according to the recommendations in (EN 15251, 2007) for category II as a sum of flow rate needed for removal of low-pollution from building materials, $q_B = 12$ L/s (0,7 L/s per m^2), and flow rate for removal of pollution from occupants, q_P (7 L/s per person). Subjects were allowed to individually control the supply airflow rate from RMP (0-13 L/s) and its direction according to their preferences. Reduced by subjects PV airflow rate was supplied by the local partition diffuser installed in the partition between WSs to keep constant supply of 26 L/s (LPD in Figure 1a). Supply air temperature was kept at all cases 3 K lower than room air temperature. There was no air recirculation in the systems. Chamber was equipped with 18 radiant panels (1190x590 mm) covering 75% of floor area. Average supply/return water temperature for chilled ceiling was 15,5/16,8°C at room air temperature of 26°C and 19,5/20,6°C at 28°C.

Solar heat gain through windows were simulated by heated water panels installed on the wall between the test room (chamber 5) and technical room (Figure 1a) and by electric foils placed at the floor under the WSs (direct solar simulation). Remaining heat sources were occupants, computers and lighting. The heat load during experiment was estimated at level of 64 W/m^2 at 26°C and 58 W/m^2 at 28°C.

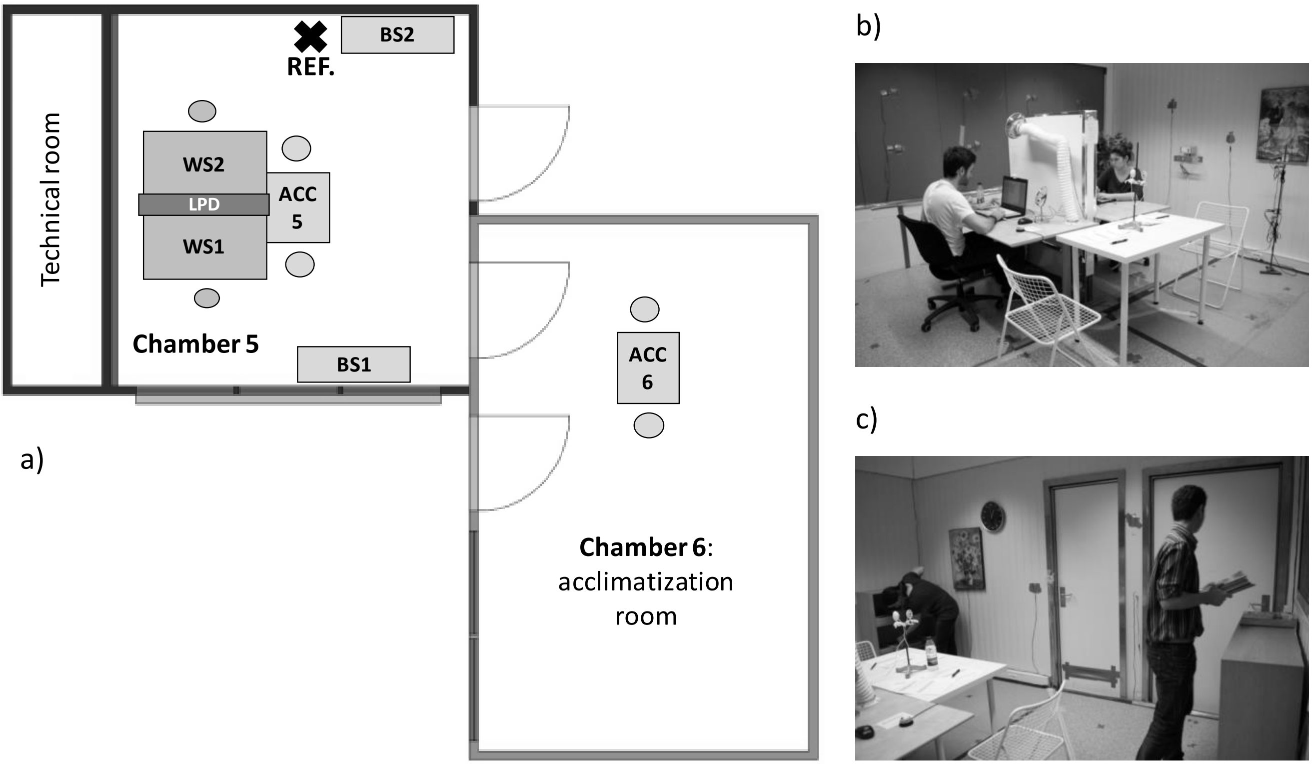

Figure 1. *Lay out of the chamber: a) plane view, b) work at the computer workstations (WS1 and WS2), c) high activity office work (BS1 and BS2)*

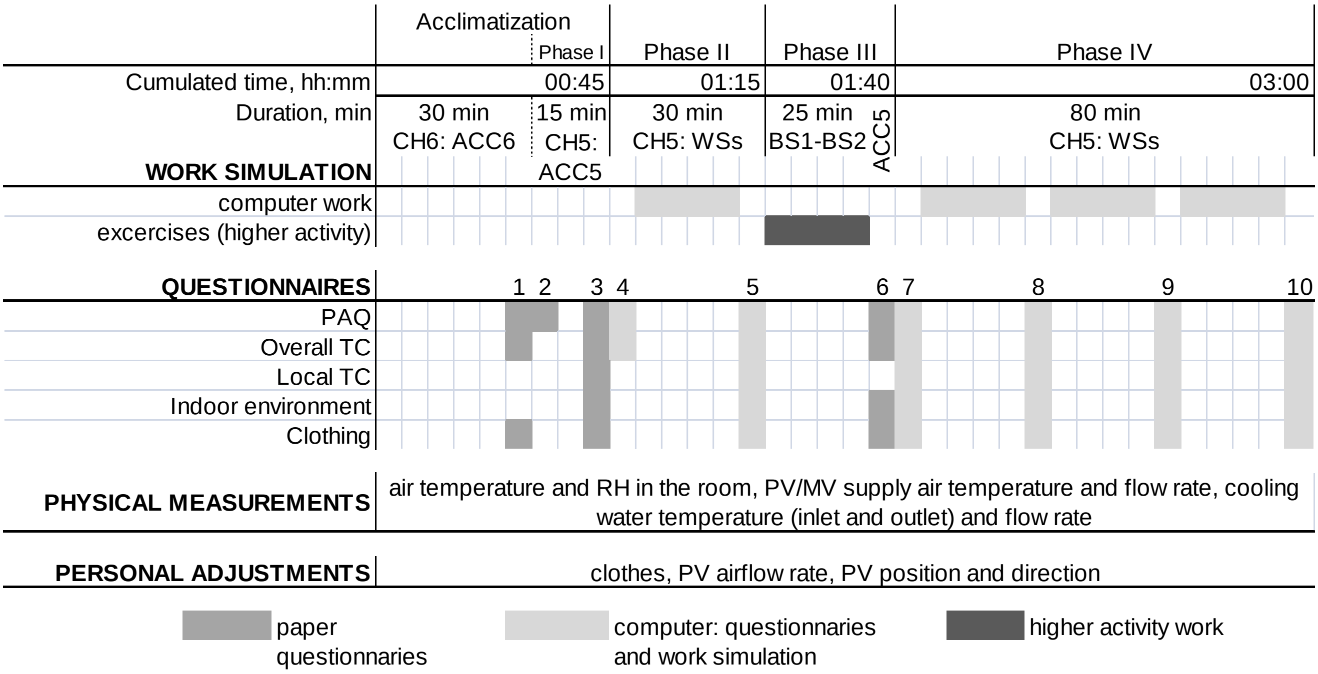

Figure 2. *Procedure during the exposure session*

Figure 2 presents the experimental procedure. For the first 30 min subjects were exposed to the uniform environment in the acclimatization room (chamber 6) after which they moved to the experimental office space (chamber 5). The temperature in both chambers was identical. Adaptation process continued for the next 15 min in chamber 5 (Phase I) at a desk next to the WSs (ACC 5 in Figure 1a). When seated at the WSs subjects performed computer tasks. After 75 min higher office activity was simulated for the period of 25 min. During this time the subjects moved magazines between bookshelves: BS1 and BS2 (Figure 1c).

Ten times during each experiment subjects filled in questionnaires. Questionnaires filled at WSs (Q4-5, Q7-10) were computerized and remaining were filled on paper. This paper focuses on influence of the systems on perceived air quality and thermal comfort. A continuous acceptability scale was used for perceived air quality evaluation. The acceptability scale ranged from "clearly acceptable" (+1) to "clearly unacceptable" (-1), with a break in the middle by points "just acceptable" (+0,01) and "just unacceptable" (-0,01). Acceptability was transferred into percentage of dissatisfied (PD) according to equation developed by Gunnarsen and Fanger (1992) and included in EN 15251 (2007). The air freshness was evaluated on a continuous scale ranging from "fresh air" (-1) to "stuffy air" (+1). For thermal comfort evaluation the 7-point ASHRAE thermal sensation scale was used (- 3 – cold, -2 – cool, -1 – slightly cool, 0 – neutral, 1 – slightly warm, 2- warm, 3 – hot) together with the acceptability scale (the same like for perceived air quality). The obtained results were statistically analysed. Shapiro-Wilk's W-test was used to test the normality of the distribution. ANOVA tests and Newman Keuls tests were applied to normally distributed data. Friedman ANOVA and Wilcoxon Matched Pair tests were used for remaining data.

3 Results and discussion

Thermal sensation and perceived air quality was assessed by subjects during each of 4 phases of experiment (Figure 2): outside WSs with sedentary activity (Phase I – questionnaire Q3), at WSs during short work (Phase II – questionnaires Q4-5), outside WSs with walking activity (Phase III – questionnaire Q6) and at WSs during longer work period (Phase IV – questionnaires Q7-10). Within the same set-point temperature no significant differences between CCPV and CCMV systems were found outside the WSs, i.e. during phases I and III.

Figure 3 presents subjects evaluation of their overall thermal sensation (OTS) during the exposure to the four experimental conditions. Median results for 24 subjects are compared. At the WSs during Phase II OTS was voted as neutral at 26°C with both systems and at 28°C with CCPV. For CCMV28 the OTS was above or equal to slightly warm sensation (1) for the whole exposure time.

The highest thermal sensation votes (1,8-2,4 – warm sensation) appeared at the end of high activity in phase III. OTS decreased during the following sedentary activity at WSs (Phase IV). At both studied temperatures thermal sensation votes decreased faster with CCPV system than with CCMV. The elevated air movement from PV caused 1,2-1,3 unit decrease at the sensation scale in 5 min after the higher activity, resulting in thermal sensation below slightly warm at both 26°C and 28°C. At CCMV26 thermal sensation dropped below slightly warm only after 30 min from the end of phase III and it came back to the level in phase II after 80 min. Similar times were observed for CCMV28.

The acceptability of thermal sensation at the WSs during phase II and IV was higher with CCPV system than with CCMV at both studied temperatures. At 26°C acceptability with CCPV was assessed by subjects 10-37% higher than with CCMV. At the case of CCPV28 acceptability was 5-27% higher at WSs than at CCMV28.

Presented results indicated that CCPV performed superior comparing to the CCMV at both studied temperatures of 26°C and 28°C. Moreover, thermal sensation at CCPV28 was similar to CCMV26 with its' acceptability up to 26% higher than at CCMV26. This suggest that increasing air temperature in the room to 28°C at CCPV system can be promising energy-saving strategy without decreasing occupants' thermal comfort.

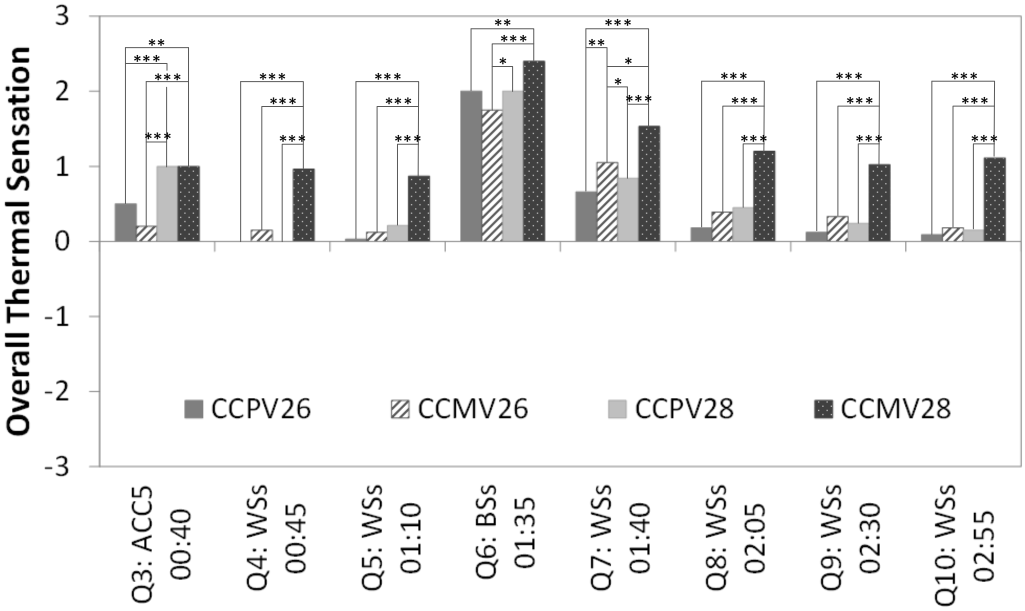

Figure 3. *Overall thermal sensation votes (significant at: * p<0,05; ** p<0,01; *** p<0,001)*

The main reason of higher acceptability of CCPV system than CCMV is the additional convective cooling by the individually controlled local air movement generated by the PV. Figure 4 presents characteristics of registered values of PV airflow rates used by subjects. After filling the first computer questionnaire (Q4) participants were asked to adjust air flow according to their preferences Shaded area in Figure 4a defines the minimum and maximum personalized airflow rate selected by the subjects and shows that subjects were choosing airflows in a wide range during whole experiment, although for most of the time the airflows above or equal to 8,5 L/s were set (Figure 4b). At CCPV28 adjusted flows were higher than at CCPV26. Average values in Figure 4a present tendency in flow adjustments. After 5 min of adjusting most of participants managed to find their preferred flows and after that the changes in the flow rate during phase II were not substantial. After high activity during Phase III the subjects moved to WS1 and WS2 and increased the supplied by PV airflow for the first 10 min. Then airflows were gradually decreased during the next 15 min to reach the value set at the end of Phase II a. Also OTS reached values declared in Phase II.

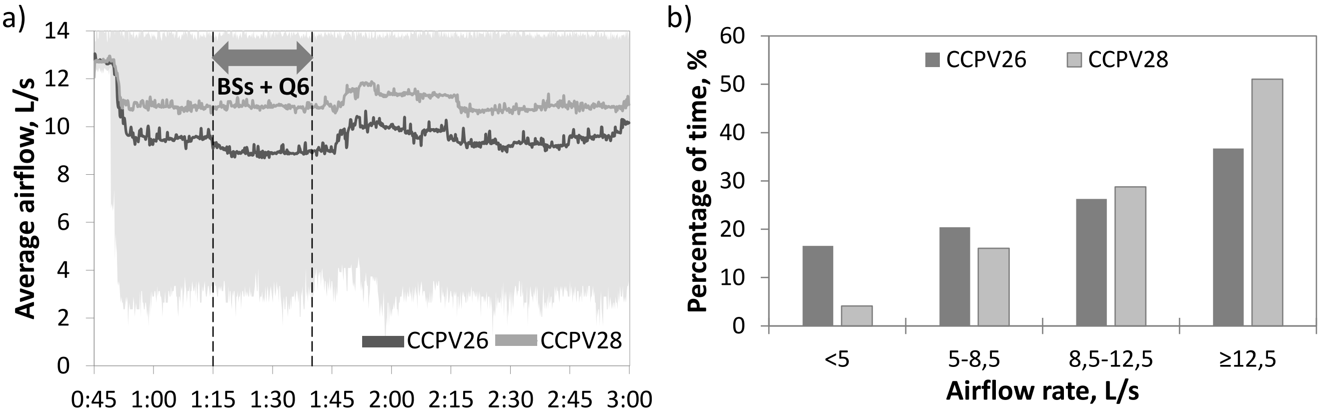

Figure 4. *Supplied PV flows: a) average airflow in time of exposure (shaded area shows range between maximal and minimal used flows), b) percentage of time individual rates in defined ranges*

The use of PV at room temperature of 26°C resulted in the lowest percentage of dissatisfied (PD) with air quality fulfilling all the time requirements for the highest category I (Figure 5). For the most of the experiments with CCMV26 and CCPV28 the level of PD was similar. Exception was registered at the entrance to the room, when at CCPV28 PD was rated unexpectedly high. Later on CCMV28 was assessed as the worst case regarding air quality. PD at this case was up to 31%.

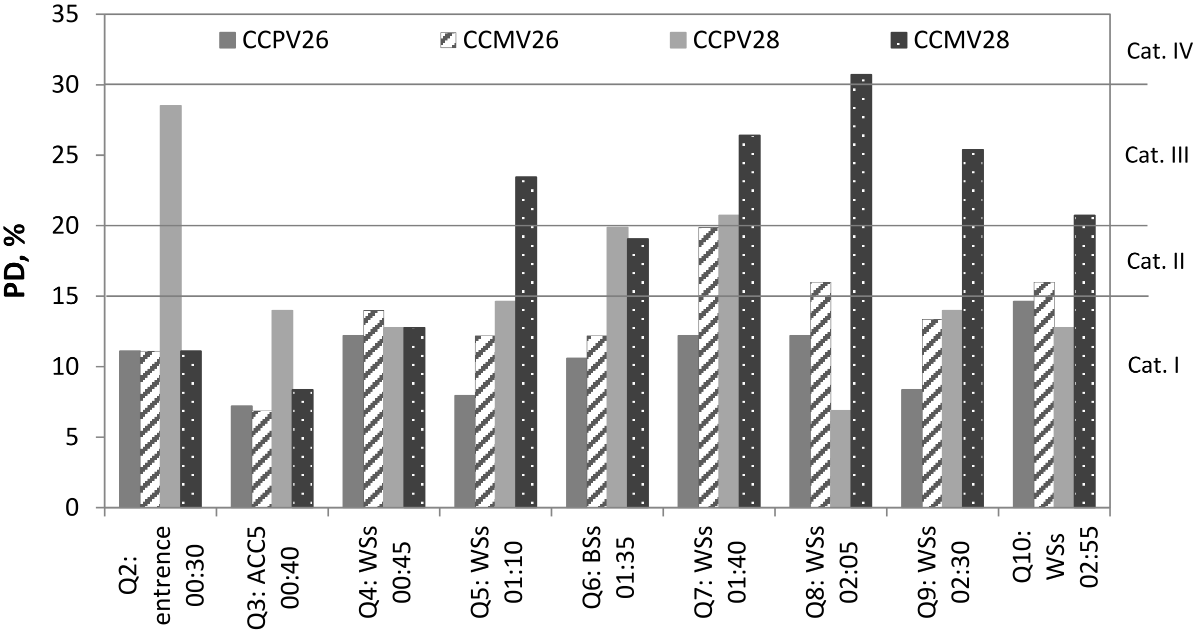

Figure 5. *Percentage dissatisfied (PD) with the air quality. Category requirements according to EN 15251 (2007)*

Figure 6 presents median votes on air freshness reported by all subjects. It can be seen that at WSs CCPV system performed superior compared to CCMV at both 26°C and 28°C. In Phase II and IV air was assessed as more fresh with CCPV than with CCMV. For the whole exposure time differences between CCPV cases and CCMV28 at WSs were significant. For first 50 min of phase IV, after high activity in Phase III, air was also significantly fresher with CCPV cases than with CCMV26. Outside WSs systems performed comparable at 26°C and 28°C. At 28°C air was assessed as stuffier than at 26°C, but without significance.

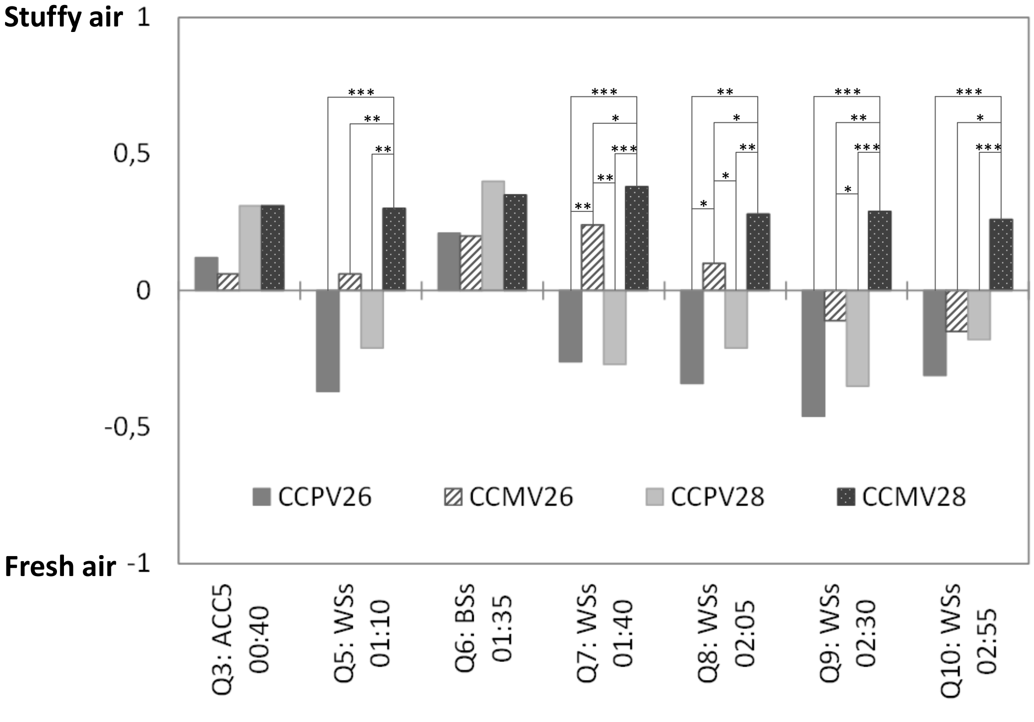

Figure 6. *Air freshness votes (significant at: * p<0,05; ** p<0,01; *** p<0,001)*

4 Conclusions

Combined system of chilled ceiling and personalized ventilation performed superior compared to chilled ceiling combined to mixing ventilation at both studied temperatures of 26°C and 28°C with regard to thermal comfort and air quality. At the workstations, where office employees spend most of the time, CCPV system created thermal condition close to neutral even at elevated temperature of 28°C. Performance of CCPV at 28°C was comparable to CCMV at 26°C. Moreover use of PV resulted in quicker improvement of thermal sensation after subjects performed higher activity work and return to steady state sensation.

Air perceived at workstation was assessed as more fresh with CCPV than with CCMV. Percentage of dissatisfied with air quality was lower at cases with CCPV system compared to CCMV.

Both studied systems created similar thermal and air quality conditions in the occupied zone outside of the workstations. Presented combined system of chilled ceiling and personalized ventilation can be successfully applied in the office building and be promising energy-saving solution.

5 Acknowledgments

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