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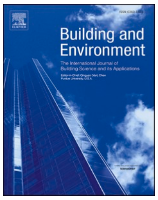

Individually controlled localized chilled beam with background radiant cooling system: Human subject testing

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ABSTRACT

This study examines the responses of twenty-four subjects to an individually-controlled localized chilled beam (LCB) and compares it to a mixing ventilation (MV) as the reference system. Both LCB and MV also used ceiling cooling (CC) panels for background cooling (forming LCBCC and MVCC systems). The LCB directed the supply air towards the subjects to create a micro-environment around them. Four experimental conditions were established using a combination of two room temperatures (26 °C and 28 °C) and two primary ventilation rates (10 l/s and 13 l/s). During the 90 min-long experiments, the subjects were asked to assess their perceived air quality, thermal sensation, comfort, air movement acceptability and acceptability of the work environment. The results indicated that the LCBCC was superior to the MVCC with significantly higher acceptability of the work environment, perceived air quality and thermal sensation. Perceived air quality and thermal sensation were rated near the "clearly acceptable" level for both room temperatures when LCBCC was used. Moreover, thermal sensation votes were close to the "neutral" level for room temperatures as high as 26 °C and 28 °C. The micro-environment established by the LCB was found to be resilient to changes in room temperature. With the MVCC, the thermal environment was rated as "slightly warm". No major potential risk of draught among the subjects was reported when using the LCBCC. The findings of this study contribute to the development of high-temperature cooling systems in general, and localized ventilation systems in particular.

1. Introduction

Nowadays, office workers spend most of their time indoors. In interior landscapes, a high level of indoor air quality and thermal comfort not only boosts individuals' satisfaction with their working environment but also leads to higher productivity [1,2]. Current practices in the design of ventilation systems often involve using centrally controlled total-volume ventilation systems. In such systems, the air is supplied to the spaces via air diffusers or air-water terminal units, such as active chilled beams (ACBs).

Total-volume ventilation systems aim to provide a uniform thermal environment for the occupants [3–5]. Due to psychological and physiological differences, it is difficult to meet the environmental preferences of individual office workers when using these ventilation systems [6]. Furthermore, the air is usually supplied from air diffusers located far from the occupants and it is already polluted before it reaches them. These ventilation systems also have a high energy demand. This is partly because they use a large amount of air to thermally condition the entire occupied space, and partly because they rely on air as the only cooling medium.

Localized ventilation is a method of room air distribution that delivers air in the occupant's vicinity. This method is primarily designed to shorten the distance between the occupants and the air diffusers, to reduce the dilution of supplied clean air before it is inhaled by occupants. Additional air movement on the face area improves the occupants' perceived air quality and thermal sensation [4,7–10]. Further

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improvement in thermal comfort and perceived air quality can be achieved if the cooling system is equipped with personal control [11–13]. Furthermore, localized ventilation systems have the potential to reduce the system energy demand, compared to total-volume ventilation systems [14,15].

Active chilled beams have been used widely for ventilation of occupied spaces [16]. The discharged air from the beam is a mix of the induced air from the room and the primary air supplied from the air handling unit. Due to the induction effect, the discharged supply airflow from an active beam can be 3–8 times higher than the primary air flow [16–18]. Thus, active beams can provide greater air movement to the occupants for the same primary airflow compared to the all-air systems. From an energy efficiency perspective, using high-temperature chilled water (>14 °C) as the main heat carrier fluid leads to higher energy efficiency [19]. It also facilitates the use of natural cooling sources, such as ground cooling systems [20,21].

The application of active chilled beams to establish a local thermal environment in a room is one of the latest solutions to facilitate the widespread adoption of localized ventilation systems [22,23]. In such application, the aim is to establish a non-uniform local-environment within the vicinity of the occupant. Therefore, instead of discharging the supply air into the room through the slots on both sides of the beam, supply air from the beam is directed towards the occupant (Fig. 2). Human subjective experiments conducted by Uth et al. [22] proved that localized chilled beams could provide an acceptable thermal environment. However, localized chilled beams could not handle the total amount of heat in the space under cooling load conditions. This could require too high airflow rate and a low temperature of the air projected to the occupants [22,23]. Both a high airflow rate and a low supply air temperature can potentially increase the risk of draughts. One way to remove a higher amount of heat from the space is to combine a water-based system with a localized chilled beam. Thus, the overall cooling capacity of the system is increased without the need for an increased airflow rate or a lower supply air temperature.

Radiant cooling panels are one of the alternatives that can be combined with the localized ventilation systems. Radiant ceiling cooling panels are part of a water-based system that utilizes the mean temperature of the panels to provide comfort cooling for the occupants [24,25]. Various studies have pointed out the low draught risk [26,27] and temperature uniformity [28] as distinctive characteristics of the spaces cooled by this system.

Research on the performance of combined radiant cooling and localized air distribution methods is limited. Chakroun et al. [29] and Mirzai et al. [30] studied the energy performance of a chilled ceiling with a displacement ventilation system assisted by a personalized evaporative cooling system. The integrated system reduced the energy demand by 21% compared to the system without personalized ventilation, yet thermal comfort was unchanged. Al-Assad et al. [31] reported that intermittent operation of personalized ventilation, combined with a chilled ceiling system at a relatively high supply water temperature (>20 °C), enhanced the users' thermal comfort and yielded a decrease of about 7%–15% in energy use. Lipczynska et al. [32,33] compared the cooling performance of radiant ceiling panels combined with personalized ventilation and mixing ventilation (MV) and reported improved thermal comfort and perceived air quality at workstations and up to 40% reduction of energy consumption. Zhao et al. [34] used over-head air diffusers to supply air directly towards the occupants in a room that was also equipped with radiant cooling panels. This system achieved lower temperatures at the workstation, considerably higher ventilation efficiency and greater energy savings as opposed to when a MV was in operation.

Previous studies assessed perceived air quality and the occupants' thermal comfort in response to localized chilled beams without using radiant ceiling panels or total-ventilation combined with radiant cooling panels. The novelty of this work lies in the application of personalized-controlled localized chilled beams integrated with ceiling cooling panels. The evaluation of this novel system was conducted first by physical measurements of the thermal environment and then by human subjective surveys. The design of the system has been improved. Further physical measurements after the human subjective surveys have been carried out to assess the performance of the finalized system. The results are compared to a reference system consisting of mixing ventilation combined with radiant cooling panels. The results of the physical measurements will be presented in a separate paper, as this paper only presents the results of the human subjective experiments.

2. Methods

This section outlines the experimental setup and the procedure for designing, conducting and analyzing the results of the subjective survey.

2.1. Experimental setup

The study was performed in two adjacent climate chambers at the Technical University of Denmark in the period mid-February to the end of March. The chambers were located in a large lab hall, wherein the temperature was kept stable at around 21 ± 1.0 °C during the experiments.

One of the chambers (referred to as chamber 6) was used as an acclimatization room for the participants in the experiments when arriving at the site with high and different activity levels (Fig. 1). The room area was 19.5 m^2 and it was cooled with a mixing ventilation system. The room temperature was kept similar to the chamber where the main experiments took place, i.e., 26 °C or 28 °C.

The main experiments were carried out in an adjacent room (chamber 5), Fig. 1. This climatic chamber had a floor area of 16.4 m^2 (4.1 m (L) × 4.0 m (W)) and a 3.1 m high suspended ceiling. Five water heated panels (0.8 m × 1.56 m) were used to simulate a window exposed to solar radiation. The floor area of the room on the side of the window (4.1 m × 2.0 m) was heated by electrical foils to generate heat gain from solar radiation. Two workstations, WS1 and WS2, where subjects were able to do sedentary office work, were arranged in the room (Fig. 1B).

Two cooling systems were available in chamber 5: localized chilled beam combined with chilled ceiling panels (LCBCC) and mixing ventilation combined with chilled ceiling panels (MVCC).

The localized chilled beam was an active beam modified by installing wing-type components. The localized beam directed the supply air towards the WS1 to establish a non-uniform local-environment in the vicinity of the workstation, Fig. 2. The discharged air was a mixture of induced air from the room through the cooling coil of the chilled beam, and primary air from the ventilation system. The primary air was taken from outside and cooled by the air handling unit. The primary airflow rate could be adjusted by the subject at the WS1 within a range from 10 l/s to 13 l/s, corresponding to the total static chamber pressure of the chilled beam between 65 Pa and 105 Pa. A higher airflow rate causes a greater pressure difference between the beam's chamber and the room, resulting in a higher water-based cooling effect of the active chilled beam. An electrical damper inside the primary air duct was connected to a control knob. The knob, placed on the table at the WS1, was used to adjust the airflow rate supplied by the LCB (Fig. 2A). Air was discharged from two sides of the beam (Fig. 2A).

The chilled ceiling was designed as water-based panels. Totally 36 panels were arranged in six parallel rows and covered about 75% of the ceiling area (Fig. 1B). The middle row was covered by lightweight fibreglass panels, ceiling-mounted lamps, and air supply diffusers.

The MV is comprised of two ceiling-mounted linear diffusers (0.1 m × 0.52 m). The supplied air had a constant rate of 13 l/s and was discharged sidewise from the diffusers, see Fig. 1B. Each diffuser was equipped with a plenum box to ensure the uniform supply air distribution.

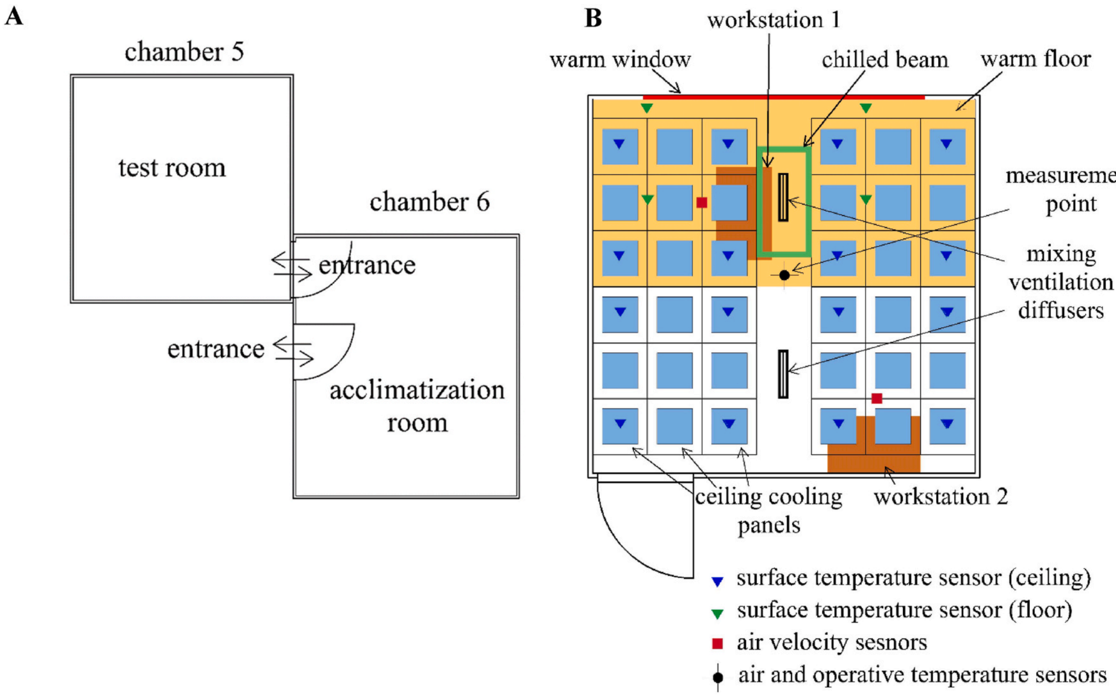

Fig. 1. A) Layout of chambers 5 and 6 and B) schematic of chamber 5.

2.2. Measurements and instrumentation

The thermal environment in chamber 5 was measured. Velocity measurements at the WS1 and WS2 were performed using low-velocity omni-directional wireless transducers (SENSOR 5100SF, Poland). The sensors measured mean air speed, which in this paper is referred to as the mean air velocity. The mean air velocity was determined based on instantaneous velocity measurements over a time interval of 300 s. The accuracy of the air velocity measurements was ±0.03 m/s within the range of 0.05–0.5 m/s air speed. The sensors were calibrated before the experiments. The sensors were installed on a tripod at eight heights (0.05, 0.1, 0.3, 0.6, 1.1, 1.4, 1.7 and 2.0 m above the floor). The measurements at the workstations were carried out without the presence of the occupant, according to ASHRAE 113 [35].

Room air temperature and operative temperature were measured using a thermistor type sensor. The air temperature sensor was shielded to protect against radiant temperature interferences. The measuring section of the operative temperature sensor was placed in a grey Ping-Pong ball, in accordance with [36]. The sensors were located at a reference point on the tripod and placed at a height of 1.1 m above the floor, see Fig. 1B. The air temperature and operative temperature were measured with an accuracy of ±0.3 °C and ±0.5 °C, respectively.

Surface temperature measurements were performed using contact thermistors. The sensors were measured the surface temperature at 16 points on the ceiling panels, 4 points on the floor, and 5 points on the warm window. Supply and return water temperature to the chilled beam and ceiling panels were also measured by this method. The sensors were attached to the surface using heat conductive paste and insulated towards the environment, as recommended by EN ISO 7726 [37]. The accuracy of surface temperature measurements was ±0.2 °C.

As already defined, the primary airflow rate to the chilled beam was adjusted by the subjects within the range of 10 l/s to 13 l/s via a control knob. Every day before and at the end of the experiments, the primary airflow rate was measured. Then, the primary airflow rate during the experiment was calculated based on the signal from the knob.

2.3. Subjects

Twenty-four university students, 12 males and 12 females participated in the experiments. All participants were in a healthy condition, non-smoker, and without allergy, asthma, or other respiratory diseases. The participants were volunteers and were paid to take part in the experiments. The anthropometric data of the subjects is listed in Table 1.

2.4. Experimental conditions

The response of the subjects to four different thermal conditions in chamber 5 was evaluated. The conditions differed in the type of the cooling system and/or room temperature set-point. The experimental conditions are summarized in Table 2.

Throughout this paper, each test condition is identified as an acronym consisting of the cooling system namely local chilled beam combined with the chilled ceiling (LCBCC) or mixing ventilation combined with the chilled ceiling (MVCC) and room set-point temperature (26 °C or 28 °C). For instance, LCBCC 26 referrers to the test performed with the local chilled beam combined with the chilled ceiling systems at the room set-point temperature of 26 °C.

Summer season room air temperature set-points were selected. According to EN 16798 [38], the room air temperature can be as high as 26 °C for class II in single offices in summer. Experiments at a room air temperature of 28 °C were also performed to investigate the possibility of energy saving when LCBCC was used in a relatively warm environment. Averaged measured room air temperature for each experimental condition is listed in Table 3.

The ventilation rates were designed based on the rates prescribed in EN 16798 [38] for a very low-polluting building in class II. The maximum flow rate of 13 l/s was calculated considering 0.35 l/s per room floor area and 7 l/s per occupant. The minimum flow rate was fixed to be 10 l/s. The induction ratio of the beam was about 3–4. Thus, the total supply of air discharged to the room was approximated between 30 and 52 l/s, depending on the primary flow rate.

Other input parameters of the system, such as primary air temperature, supply water temperature, supply water flow rate, internal heat gains, etc. were calculated based on the heat balance of the room to

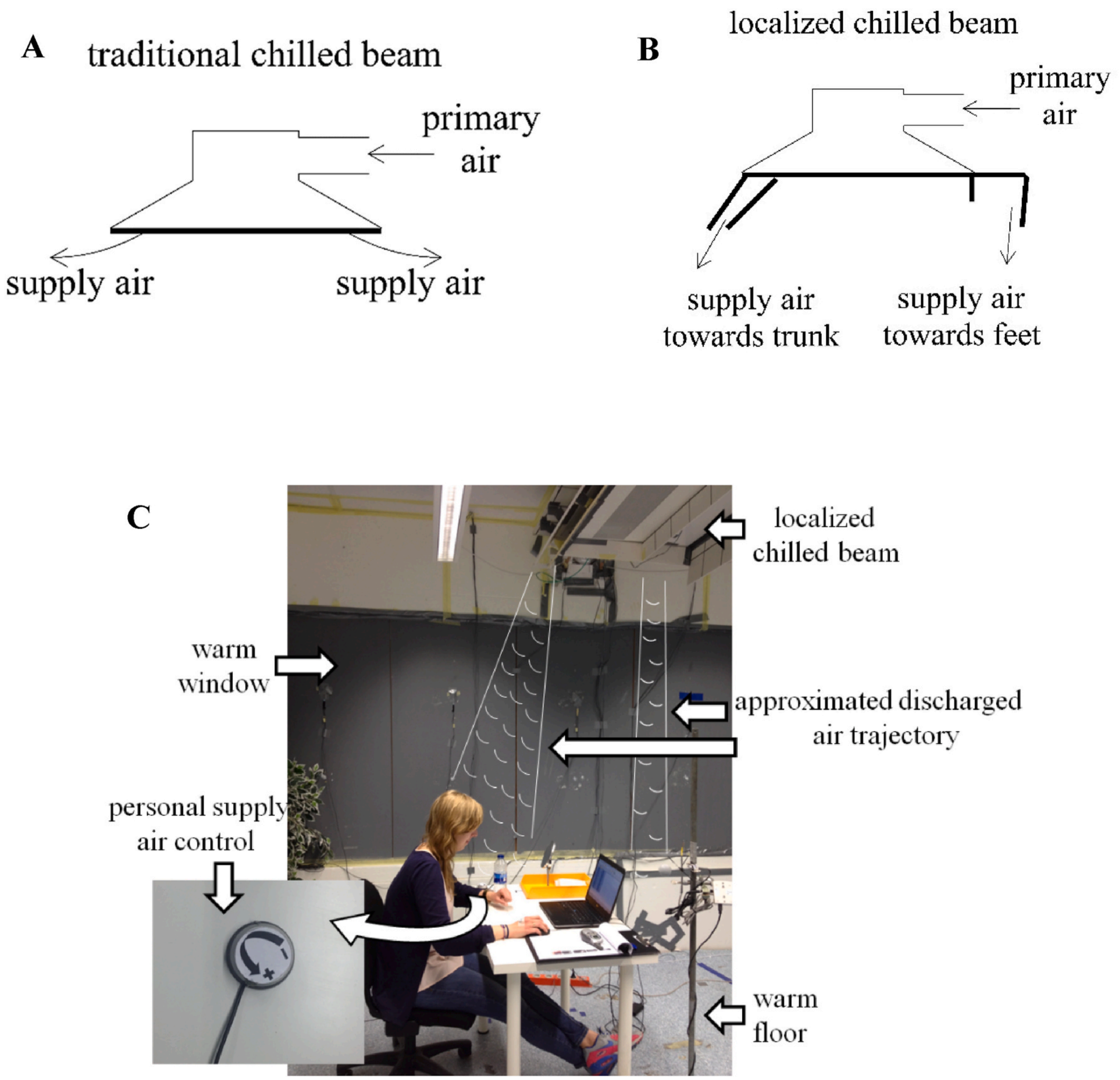

Fig. 2. A) Schematic of a traditional active chilled beam, B) schematic of the localized chilled beam used in the experiments, C) Photo of the experimental setup at workstation 1.

Table 1
Anthropometric data for the subjects.

Gender	Males	Females	Males and females
Weight (kg)	77.5 ± 10.5	63.1 ± 8.9	70.3 ± 9.7
Height (m)	185 ± 5.8	170.9 ± 7.0	177.9 ± 6.4
Age (years)	23.7 ± 2.0	24.3 ± 1.6	24.0 ± 1.8

Table 2
Test conditions.

Condition	System	Set-point temperature (°C)	Primary airflow rate (l/s)
LCBCC 26	Chilled beam and cooling panels	26	10- 13 (individual control)
LCBCC 28	Chilled beam and cooling panels	28	10- 13 (individual control)
MVCC 28	Mixing ventilation and cooling panels	28	13 (no individual control)
MVCC 26	Mixing ventilation and cooling panels	26	13 (no individual control)

reach the set-points. The averages of the parameters maintained during the experiments are summarized in Table 3.

The overall heat gain without the presence of occupants was kept constant (976 ± 14 W) for all experiments, as summarized in Table 3. The overall heat gain included heat from the warm window (405 ± 6 W), electrical foils on the floor (266 ± 13 W), one laptop (20–30 W), and four light fittings (280 W). The configuration of the heat gain sources is shown in Fig. 1B.

2.5. *Experimental procedure*

The subjects were divided into 6 groups of four people. Each group participated in four experiments. The experiments' order was arranged randomly, and the test conditions were not disclosed to the participants. All group members participated in the same experimental condition on the same day but at different times, Monday to Saturday from 8:00 to 16:00. Each experiment took 90 min, including an acclimatization period of 30 min in chamber 6 and an exposure period of 60 min in chamber 5.

The subjects were first acclimatized for 30 min in a room adjacent to the test chamber, Fig. 1A. The acclimatization period aimed to minimize the effect of outdoor climate conditions on the thermal sensation of the

Table 3
Average (standard deviation) measured values for operation parameters in four experimental conditions.

Condition		LCBCC 26	LCBCC 28	MVCC 28	MVCC 26
Primary air temperature (°C)		15.1 (±0.1)	15.1 (±0.2)	15.3 (±0.2)	14.5 (±0.2)
Primary airflow rate (l/s)	Min	10.9 (±1.0)	10.5 (±0.5)	13.9 (±0.6)	13.9 (±0.5)
	Max	13.5 (±1.1)	13.2 (±0.2)		
WS1 temperature (°C)	Operative	26.4 (±0.2)	28.4 (±0.2)	28.3 (±0.1)	26.3 (±0.2)
	Air	26.2 (±0.2)	28.1 (±0.1)	28.1 (±0.1)	26.1 (±0.)
WS2 temperature (°C)	Operative	26.4 (±0.2)	28.4 (±0.1)	27.9 (±0.3)	25.8 (±0.2)
	Air	26.3 (±0.2)	28.4 (±0.1)	27.7 (±0.1)	25.7 (±0.2)
Relative humidity (%)		26 (±2)			
Chamber 6 air temperature (°C)		26.4 (±0.2)	28.2 (±0.2)	28.2 (±0.3)	26.2 (±0.3)
Average LCB inlet water temperature (°C)		21.2 (±0.1)	21.3 (±0.0)	–	–
Average CC inlet water temperature (°C)		17.1 (±0.0)	21.4 (±0.1)	15.9 (±0.1)	21.7 (±0.0)
Average ceiling surface temperature (°C)		20.1 (±0.8)	24.0 (±0.6)	22.6 (±0.2)	19.0 (±0.2)
Average simulated window temperature (°C)		34.7 (±0.6)	35.8 (±0.7)	35.5 (±0.6)	34.9 (±0.8)
Average floor temperature (covered by the electrical foils) (°C)		31.2 (±0.3)	31.3 (±0.2)	32.8 (±0.8)	30.6 (±1.0)
Average floor temperature (not covered by the electrical foils) (°C)		26.0 (±0.2)	28.0 (±0.2)	27.4 (±0.1)	25.4 (±0.2)
Internal heat generation (W/m^2)		59.5 (±0.9)			

participants, as it was also used in other studies [39–41]. In addition, the acclimatization period helped to reduce the effect the increased metabolic rate of the occupants on their thermal conditions when arriving at the test location by means of public transportation or cycling. The air temperature in the acclimatization room was the same as in the test room. During the acclimatization period, the subjects could adjust their clothes, drink water, and do light office works such as web browsing. Meanwhile, they were asked to fill in a questionnaire at certain times, as shown in Fig. 3.

After spending 30 min in the acclimatization room, the subject proceeded into the test room. The total test period of 60 min was divided equally into two portions of 30 min at each workstation. During the test, the subjects completed questionnaires at certain times, as shown in Fig. 3. They were encouraged to modify their clothing to feel thermally comfortable.

2.6. *Questionnaires*

Questionnaires were used to assess the subjective perception of overall body thermal sensation (OTS) and local thermal sensation (LTS) and their acceptability, perceived air quality (PAQ) and its acceptability, clothing type, and local air movement and its acceptability. The body parts investigated were head, face, neck, chest, back, arms and hands.

Acceptability of PAQ was assessed using a two-halves continuous-scale questionnaire with endpoints ranging from - 1.0 (clearly unacceptable) to - 0.01 (just unacceptable) and from +0.01 (just acceptable) to +1.0 (clearly acceptable), as suggested by Gunnarsen and Fanger [42] and ISO 7730 [37]. A similar questionnaire was used to assess the acceptability of thermal sensation.

OTS and LTS were evaluated using continuous ASHRAE 7-point scale: coded from cold (−3) to hot (+3), ASHRAE 55 [43]. The questions on air movement included: perception of air movement on each body part (Yes/No), its acceptability (similar scale as PAQ acceptability), and preference for air movement (more, less or no change of air movement). Questions on the worn clothing type were asked three times during the experiment. Every piece of clothing was coded and used to calculate the overall clothing value for each person at each session of the experiment (ASHRAE 55 [43]).

2.7. *Data analysis*

Normality distribution of the human subjective data was subjected to the Shapiro-Wilcoxon test with a significance level of $p < 0.05$. In the case that data was not normally distributed, non-parametric tests were used to analyze the results. Since in the present study the same group of people was exposed to different thermal conditions established by the cooling systems, variables in the experiment had a dependent relationship. Therefore, two groups of results were compared as dependent variables using Wilcoxon matched pairs test, with the significance level of 0.05.

Primary airflow and water flow rates, surface temperatures, relative humidity of the air, room air, and operative temperatures and electricity to the heat gain sources were continuously measured during each human subjective test with an interval of 300 s. An average of the measurements under a similar experimental setup was used for data analysis.

Instantaneous velocity and temperature of the air at the WS1 and WS2 were measured and recorded at each height over 300 s interval. An average value was reported for each height.

3. Results

3.1. *Clothing*

Fig. 4 shows the average clothing value of the subjects during the

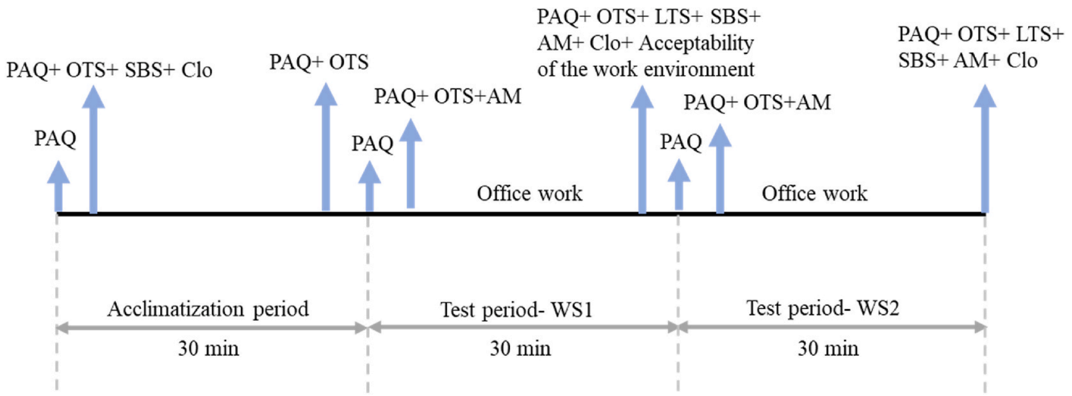

Fig. 3. Experimental procedure: questionnaires to assess perceived air quality (PAQ), overall thermal sensation (OTS), local thermal sensation (LTS), sick building syndrome (SBS) symptoms, air movement (AM) and clothing (Clo) by the subjects.

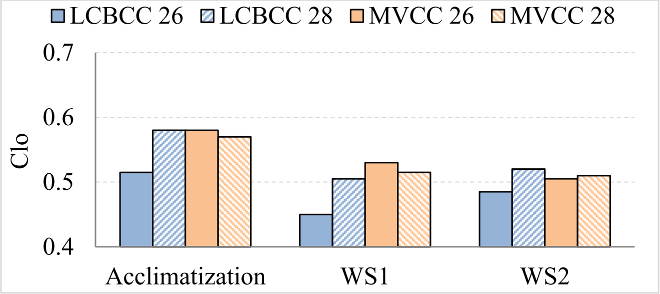

Fig. 4. Average clothing (clo) during the acclimatization and the test periods.

experiment. Each piece of clothing was scaled based on thermal insulation provided for the body according to Ref. [44]. Then, the average value was calculated for each subject during one test. The overall clothing value for each experimental condition was the median of the data set for all participants. No significant difference ($p > 0.01$) in the average clothing values was found between male and female subjects. Small standard deviations in all cases imply minor clothing adjustment during the test period.

It is difficult to define a general trend in clothing over the whole experiment because of insignificant differences between the values. However, the highest values appear during the acclimatization period, owing to the high metabolism of the subjects upon arrival. For cases with the LCBCC, clothing values are relatively lower at the WS1 than the WS2. When using the MVCC, no modification in clothing can be seen.

3.2. Overall thermal sensation (OTS)

The additional convective cooling provided by the LCBCC at the WS1 had two important advantages for occupants' OTS. Firstly, it reduced the influence of longwave radiation from the nearby heat sources, i.e. warm window and floor. Indeed, the additional convective cooling helped to achieve OTS close to neutral by increasing air movement over the human body. In the absence of local cooling when MVCC was operating, occupants tended to feel slightly warm, see Fig. 5. Secondly, the OTS of the occupants at the WS1 was resilient against changes in the room temperature. OTS increased from +0.0 to +0.2, yet remained in the neutral range, by increasing the room temperature from 26 °C to 28 °C. However, OTS increased from +0.5 to +1.0 and fell into the slightly warm thermal sensation range with MVCC.

The WS2 was located away from the warm window and warm floor by approximately 4 m and 3 m, respectively. Thus, the subjects' thermal sensation was less affected by longwave radiation from those sources. However, they felt slightly warmer at the WS2 than the WS1 when LCBCC was in operation. This indicates that the additional convective cooling by the beam mitigated the effect of the warm window and floor at the WS1.

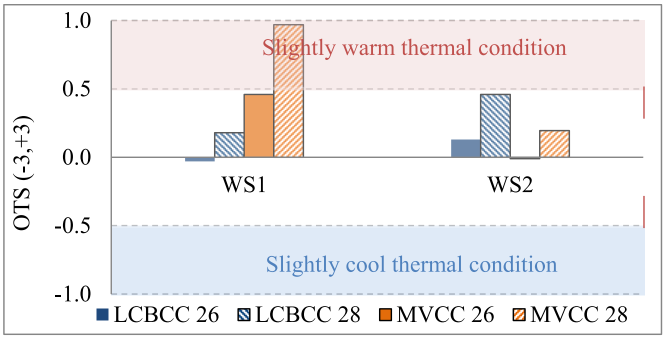

Fig. 5. The median value for overall thermal body sensation (OTS) obtained at workstation 1 (WS1) and workstation 2 (WS2). The thermal sensation scale is: −3 – "Cold", −2 – "Cool", −1 – "Slightly cool", 0 – "Neutral", 1 – "Slightly warm", 2 – "Warm", 3 – "Hot".

When MVCC was in operation, occupants to felt significantly cooler ($p < 0.05$) when moving from the WS1 to WS2. This was partly due to the increased distance from the heat sources but mainly because of the downward airflow at the WS2. The strong upward buoyancy flow, generated by the warm window and warm floor, pushed the supply air from the ceiling diffusers toward the opposite wall where the WS2 was located. Then, the airflow reached the wall and deflected down toward the occupant. The downward airflow had a speed of 0.18–0.22 m/s around the head level at the room temperatures of 26 °C and 28 °C, respectively. This elevated air speed enhanced the convective cooling effect of the occupant.

Fig. 6 shows the OTS acceptability at the WS1 and WS2. The OTS votes were evaluated by the subjects after 25 min being at each workstation. The thermal acceptability scale ranges from "clearly unacceptable" (−1) to "clearly acceptable" (+1).

OTS acceptability for all cases was evaluated within the range of just acceptable (+0.01) to "clearly acceptable" (+1.0). However, the votes seem to be in favour of LCBCC. For similar room temperature at the WS1, a significantly higher OTS acceptability level ($p < 0.05$) was achieved with LCBCC owing to the influence of additional air movement and cooling effect by the localized beam. Also, note that the thermal condition at the WS1 was highly affected by the warm window and floor. However, subjects' votes show a similar acceptability level at both workstations. This points out the potential of the localized beam to reduce the effect of the nearby heat sources so that the occupants' thermal perception would be similar to that without the heat sources.

3.3. Local thermal sensation

The local thermal sensation of the upper human body parts was reported by the occupants at the end of the test period at the two workstations. The thermal sensation votes of the body parts exposed to the local-thermal environment generated by the LCBCC were within the range of ±0.5 (neutral), Fig. 7A. Increasing the room air temperature from 26 °C to 28 °C caused a slight increase in the LTS of all body parts. However, all the LTS votes yet remained close to the 0.0 thermal sensation level. This indicates the stability of the thermal environment with the LCBCC against the changes in the room temperature. On the other hand, an increase in the room temperature caused a considerable increase in the LTS votes so that the thermal sensation of all upper body parts fell into the slightly warm range (+0.5), Fig. 7A.

Arms and hands (left and right) appeared to be the coldest body parts under all experimental conditions at the WS1. Being out of the convective plume of the body and being exposed to the supply air from

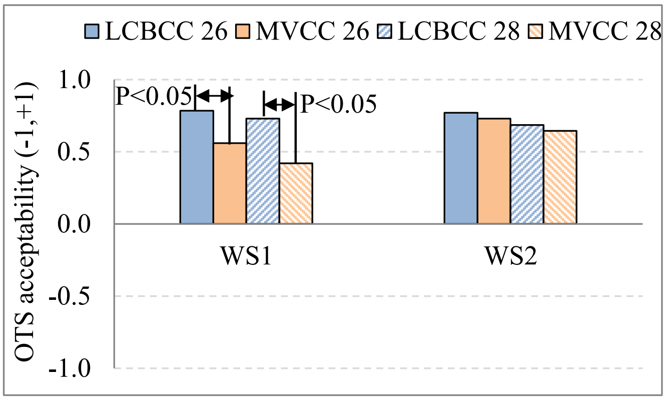

Fig. 6. The overall thermal sensation (OTS) acceptability of the occupants after spending 30 min at workstations 1 (WS1) and workstation 2 (WS2). The thermal acceptability scale is −1 – "Clearly unacceptable", −0.01 – "Just unacceptable", 0.01 – "Just acceptable", 1 – "Clearly acceptable".

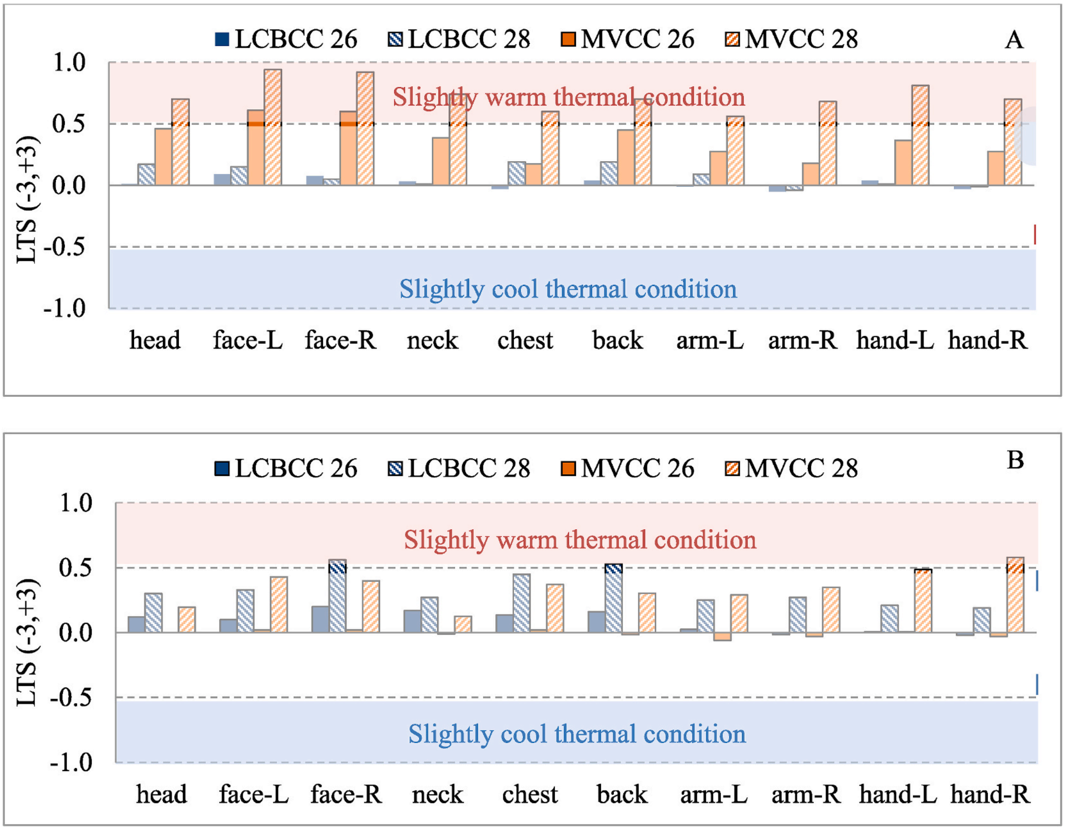

Fig. 7. Local thermal sensation (LTS) votes of upper body parts at A) workstation 1 (WS1), and B) workstation 2 (WS2). The scale is: −3 – "Cold", −2 – "Cool", −1 – "Slightly cool", 0 – "Neutral", 1 – "Slightly warm", 2 – "Warm", 3 – "Hot".

the localized beam were the main reasons for the lower thermal sensation in arms and hands. It can also be seen (Fig. 7A) that increasing the room temperature hardly affected the LTS of the arms and hands. This indicates that the cooling effect of the localized airflow was sufficient to mitigate the heating effect of the warm window. The LTS votes for arms with MVCC increased from the neutral to the slightly warm condition when the room temperature increased.

LTS votes show that occupants found the WS2 cooler than the WS1 when MVCC was operating. One reason was the low impact of the warm floor and the warm window on the thermal sensation of the occupants at the WS2. Another reason was that the downward flow of supply air at the WS2 increased the convective cooling on the occupants when MVCC was operating. LTS votes increased towards the slightly warm level with an increase in the room temperature. With MVCC, the downward air speed increased from 0.18 m/s at 26 °C to 0.22 m/s at 28 °C. As opposed to the controlled airflow supplied from the LCB, this airflow was an unintentional air stream in the room and its speed and temperature were not controlled. Thus, its cooling effect was not sufficient to stabilize the LTS. Arms and hands were found as the coldest body parts, due to the same reasons as previously explained in this section for WS1. No difference can be seen in the LTS of the right and left arms and hands because of the uniform thermal condition at the WS2.

3.4. Perceived air quality

Fig. 8 compares the acceptability of perceived air quality (PAQ) evaluated at the WS1 and WS2. At both workstations, subjects evaluated the PAQ within the acceptable range, i.e. from "just acceptable" (+0.01) to the "clearly acceptable" range (+1.0). Votes at the WS1 showed that air was perceived as more acceptable by the subjects when using LCBCC. The increase in the room air temperature from 26 °C to 28 °C had no influence on PAQ votes for the conditions with LCBCC. On the contrary, PAQ deteriorated by 0.2 for the same room temperature increase when using the MVCC. Statistical analysis shows a significant difference ($p < 0.01$) between the acceptability of air quality in the case of LCBCC and MVCC. Better PAQ in the case of LCBCC compared to the MVCC can be attributed to the local air movement provided by the localized beam [8].

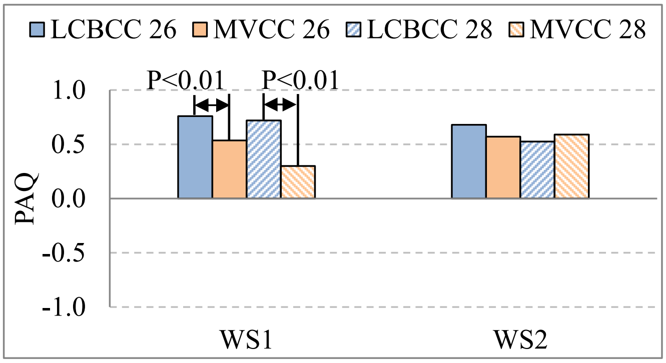

Fig. 8. *Perceived air quality (PAQ) acceptability at workstation 1 (WS1) and workstation 2 (WS2) evaluated at the end of the* 30 min *test period. The acceptability scale is -1 – "clearly unacceptable", -0 – "just unacceptable", +0 - "just acceptable", and +1 - "clearly acceptable".*

PAQ votes at the WS2 ranged from +0.5 to +0.7 under the tested conditions. No statistically significant difference was observed between the cases. When using the LCBCC, PAQ changes inversely with the room temperature changes, i.e., the lower the room temperature, the higher the PAQ at the WS2. It is also important to note that the occupants had no control over the airflow at the WS2, as opposed to the controlled airflow at the WS1. Having control over the flow rate likely caused an improvement in PAQ.

The results also show that relatively high air velocity (~0.2 m/s) at the WS2 when using the MVCC did not improve PAQ votes compared to that with the LCBCC. The airflow direction at the WS2 was downward and opposite to the upward thermal plume from the occupant's body. It was possible that the air speed was not sufficient to push away the thermal plume and reach the breathing zone of the occupant.

3.5. Airflow control and air movement sensation

Subjects at the WS1 were able to adjust the primary airflow rate to the active beam via using a desk-mounted control knob. The airflow rate ranged from 10 l/s to 13 l/s. According to the technical characteristics of the beam, the induction ratio is approximately 3–4. Therefore, 3 l/s change in the primary air increased approximately 10 l/s of the supply flow rate from the beam.

Fig. 9 shows the vertical air velocity distribution at the WS1 where occupants were seated. The measurements were carried out for the minimum and maximum primary airflow rates. The measurements show clearly the increase of the local air movement in the case of LCBCC compared to the case of MVCC. The expected increase of the local air movement when the primary flow rate was changed only by 3 l/s, i.e. from 10 l/s to 13 l/s, is also clear from the results. The highest air velocity was measured at 1.10 m. The LCBCC generated air movement with the elevated velocity at the head region of the person at the WS1.

Fig. 10 presents the frequency of the airflow rates adjusted by the subjects in the last 10 min of their stay at the WS1 when exposed to the LCBCC. Regardless of the room temperature (26 °C or 28 °C), more than 70% of the subjects adjusted the airflow rate at the maximum level providing local air movement with the mean velocity at the head around 0.35 m/s. Still, 30% of the subjects preferred lower velocity.

The number of subjects who perceived air movement on different body parts while seated at the WS1 is shown in Fig. 11A. As expected from the air velocity measurements (Fig. 9), air movement was perceived on the face and head. Only 9 subjects (37%) perceived air movement on the neck. This low percentage can be attributed to the difficulty of the discharged jet reaching the neck of the seated subjects. Surprisingly, the influence of the air movement was not only strong on the face and head, where the maximum velocity was measured, but also on the arms and hands. Smoke visualization performed with a thermal manikin resembling average size Scandinavian woman revealed that the trunk of the seated manikin directed the airflow towards the desk where hands and arms were located. The air movement was not perceived on the chest, since it was covered by T-shirt.

Comparing the results with LCBCC at the WS1 and the WS2 in Fig. 11 shows a considerable drop in the number of subjects perceiving air movement when seated at WS2. Only a few subjects (<3) recognized air movement on different body parts. This result indicates that air movement did not have a major role in forming the thermal environment at the WS2 in conditions with LCBCC. On the other hand, the air movement was more distinguished at the WS2 compared to the WS1 with MVCC, due to the influence of the downward airflow at the WS2 (Fig. 11B).

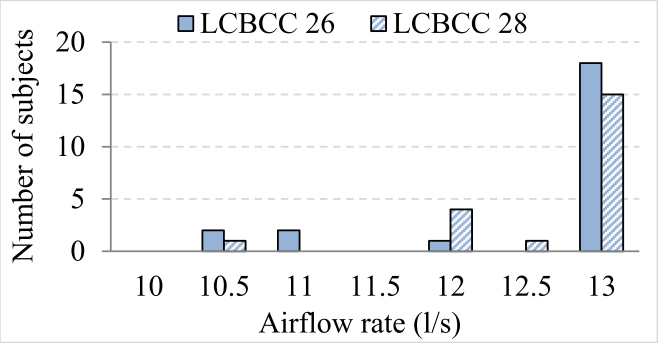

Fig. 10. Adjusted airflow rate at WS1 during the last 10 min of the exposure period.

Fig. 12A shows the acceptability of air movement when subjects were at the WS1. Both at 26 °C and 28 °C, subjects' acceptability was lower in most of the body parts when exposed to MVCC compared to LCBCC. Subjects preferred more air movement in the case of MVCC. The acceptability of air movement decreased with an increase of the room temperature, indicating the preference for more air movement when exposed to the two system configurations. The improvement in air movement acceptability with the LCBCC was clear at 28 °C. At 26 °C, the differences in the acceptability of the local air movement between LCBCC and MVCC were small.

Fig. 12B shows the acceptability of air movement when subjects were at the WS2. More subjects perceived air movement with the MVCC (Fig. 11B). However, the air movement acceptability votes are comparatively similar to two systems for the same room temperature. Thus, it is likely that the downward flow at the WS2 did not play an important role in improving the air movement acceptability of the subjects.

During the analysis of the frequency of airflow rate adjusted by the occupants, it was found out that the subjects did not adjust the airflow rate after a few numbers of attempts at the beginning of each test period at the WS1. Combining the results of LTS (Fig. 7), air velocity measurements (Fig. 9) and the frequency of adjusting the airflow rate by the occupants (Fig. 10) may explain this behaviour. One reason could be that the subjects felt comfortable with the maximum airflow rate so that they did not want to change their thermal environment. Since the distance between the subjects and the chilled beam was about 2.0 m, small

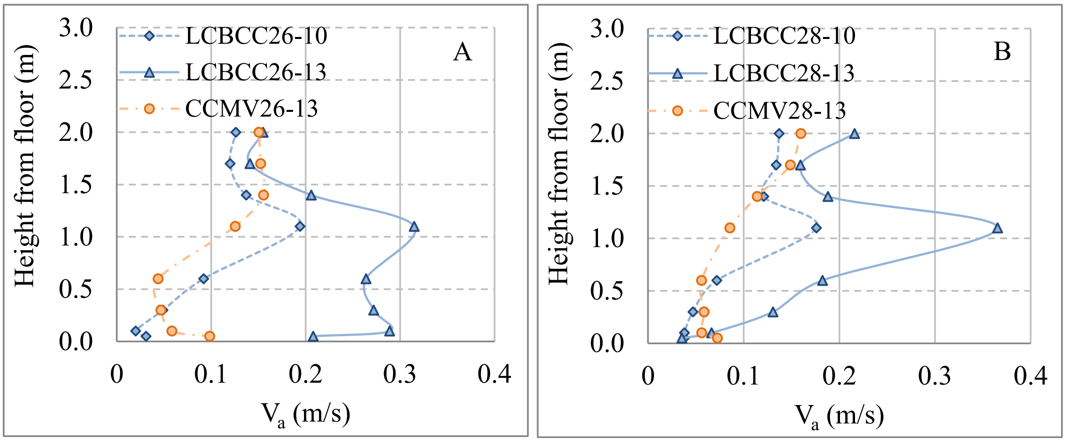

Fig. 9. Vertical air velocity distribution at WS1 with the minimum (10 l/s) and maximum (13 l/s) airflow rates at A) 26 °C and B) 28 °C.

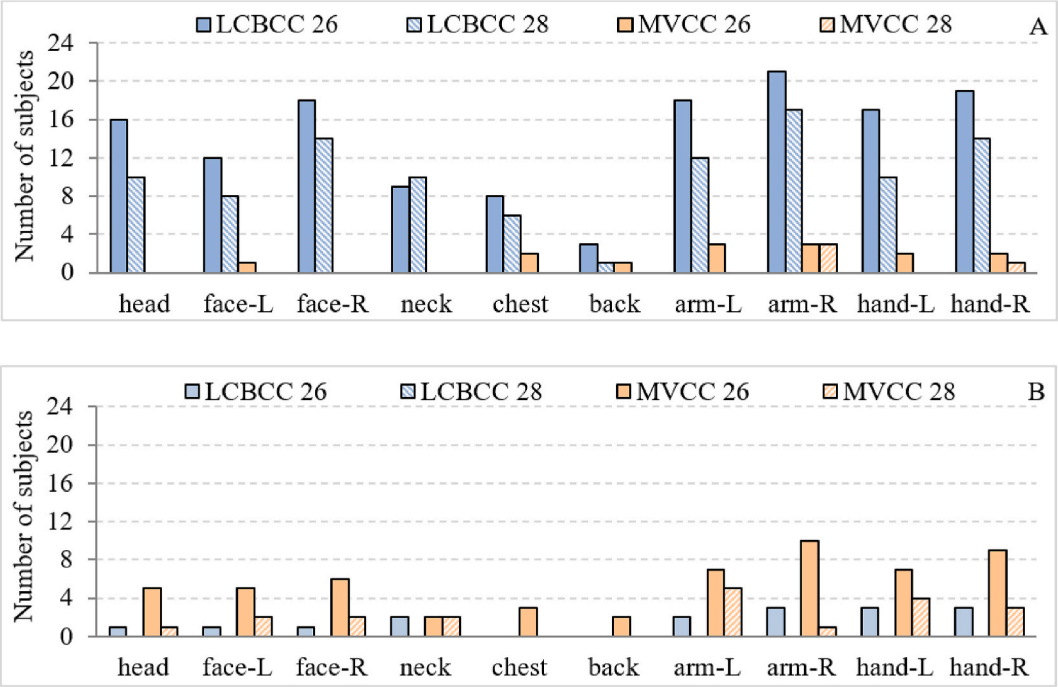

Fig. 11. The number of subjects perceived air movement on the upper body parts at A) WS1 and B) WS2.

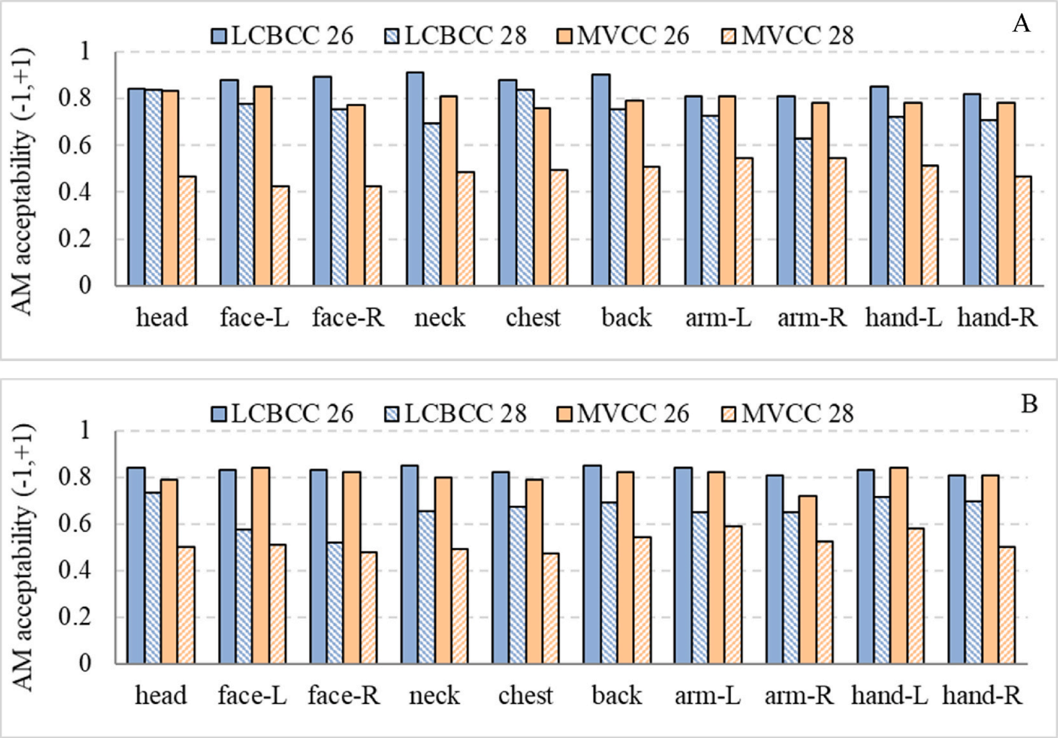

Fig. 12. Air movement (AM) acceptability at different body parts at A) WS1 and B) WS2. The scale is −1 – “clearly unacceptable”, 0- – “just unacceptable”, 0+ –” just acceptable”, +1 –” clearly acceptable”.

changes in the supply air velocity from the beam were not clearly perceived by them. Another reason could be that the deviation in subjects’ sensation was not great enough to force them to change the airflow rate. Moreover, similar votes of LTS and air movement acceptability imply that the subjects were generally satisfied with the local environment generated by LCBCC at the WS1, regardless of the differences in the adjusted airflow rate. Other reasons could be that the airflow adjustment was not prioritized by the subjects, or the subjects were adopted to the indoor thermal condition.

3.6. Draught discomfort

Draught, defined as undesirable local cooling of the body due to air movement, is the most common thermal discomfort factor in spaces cooled by air [37]. In this study, draught discomfort was expected for the subjects with LTS of slightly cool or cold on one of their upper body parts and wish for less air movement on that particular body part. Thus, all LTS votes and air movement acceptability votes within these criteria were analyzed to investigate the prevalence of the draught discomfort.

At 26 °C room air temperature, 4 votes (15% of the whole study group) indicated a slightly cool sensation on the left arm and 6 votes (25% of the whole study group) on the right arm. None of the subjects reported cold LTS on any body parts. Considering the air movement preference votes, four subjects (15%) with LCBCC 26, 2 subjects (8%) with LCBCC 28, and two subjects (8%) with MVCC 26 appeared to feel slightly cool and preferred less air movement. In the next step results from air movement acceptability and LTS acceptability were considered. It turned out that the draught risk was likely for only 2 of the subjects under the LCBCC 26 condition. Both subjects were female and within the same-age range. Analyzing the results from the adjusted supply airflow rate revealed that only one of the two subjects reduced the flow to the minimum. The other subject kept the airflow rate always above 12 l/s. Interestingly, this subject increased the airflow rate from 11 l/s to 12.6 l/s during the last 20 min of the experiment.

According to the above, it is likely that only 1 subject (4% of the study group) experienced draught when the LCBCC was in operation. Therefore, the potential risk of draught should not be significant. It is worth noting that people's preferences for air movement significantly varies so that a desirable air movement for one person is intolerable for another one [45]. Thus, the subject, who likely experienced draught, might be too sensitive to air movement.

3.7. *Acceptability of the working environment*

Subjects' responses can be used to evaluate the thermal condition of the working environment (EN 16798 [38]). The occupants evaluated the thermal environment on a two-half continuous scale, ranging from "clearly unacceptable to just unacceptable" and "just acceptable" to "clearly acceptable". The question was asked once at the end of the test period at the WS1.

As shown in Fig. 13, the acceptability of the working environment was significantly influenced by the cooling system used. For the thermal conditions tested, the acceptability was significantly higher with the LCBCC system. The highest acceptability (0.77) was reported at room temperature of 26 °C. In comparison with the MVCC, using the LCBCC caused increased acceptability by 0.3 and 0.45 scale units at 26 °C and 28 °C, respectively. The influence of air movement on the acceptability of the working environment increased with the increase of the room temperature.

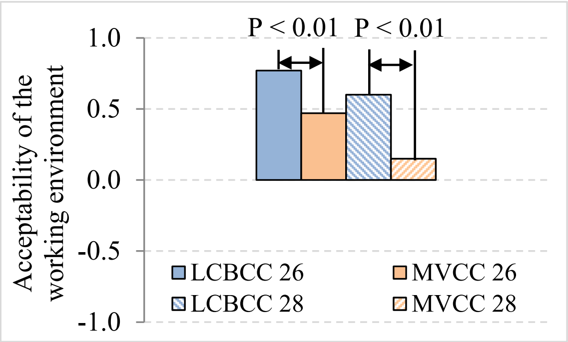

Fig. 13. Median votes on the acceptability of the working environment. The scale is −1 – "Clearly unacceptable", 0 – "Just acceptable/unacceptable", and +1 – "Clearly acceptable".

4. Discussion

4.1. *General discussion*

Localized systems and personal controls have been developed to reduce the conditioning area from the whole room to a smaller area close to the human body. Potential benefits of implementing these systems include reduced energy demand, and improved PAQ and thermal comfort [15,37] and inhaled air quality [4,6,7]. The main goal of this study is to investigate the influence of the non-uniform local-environment generated by the localized chilled beam on subjects' thermal comfort and PAQ. Particular attention has been paid to investigating the effectiveness of personalized control on PAQ and thermal comfort under room temperatures as high as 28°.

Our results showed that PAQ remained at the "clearly acceptable" level at both 26 °C and 28 °C when using the LCBCC. In contrast with MVCC, PAQ significantly deteriorated for the same room temperature increase. This result concurs with the findings reported by Fang et al. [46]. The LCB elevated the air movement around the head region of the subjects. The positive influence of air movement on PAQ can be explained as a combined effect of different factors. As discussed in Refs. [8,47,48], elevated air movement increases the convective and evaporative cooling around the nose region. Another reason may be the disruption of the human thermal plume by the supply air from the beam. The free convection thermal plume around the human body carries bio effluents and negatively affects the inhaled air quality. If supplied at an appropriate velocity, facial air can peel off the thermal plume and prevent the bio effluents from reaching the breathing zone [49,50].

In this study, changes in PAQ are mostly associated with the facial air movement from the LCB and/or the thermal environment at the workstations. Air movement and indoor temperature influence the air acceptability and air freshness of the perceived air. However, sick building syndrome and odour intensity remain almost intact [51]. The LCBCC would have a greater improvement in PAQ if pollution concentration in the room were higher. In fact, the LCB can be leveraged to the maximum extent in a space with a high percentage of dissatisfaction with PAQ [8]. Further research is suggested to study the influence of LCB on the PAQ of the occupants with the presence of a pollution source.

Occupants' thermal sensation at the WS1 was a result of thermal interactions between the heat gains (warm floor and warm window) and the cooling systems. The LCB at the WS1 established a non-uniform environment by elevating the air speed on the upper body parts, especially around the head and face areas. Elevated air speed increased the convective cooling of the body parts exposed to the airflow. Thus, LTS votes of the investigated upper body parts were generally closer to the neutral level with the LCBCC than that with MVCC. A similar trend can be seen in OTS. In other words, OTS votes closely follow the LTS votes. Furthermore, in neutral and cool non-uniform thermal conditions, the LTS of the head region strongly influences the OTS of the occupants [52,53]. Thus, the facial airflow by the LCB can further improve the LTS of the occupants and hence, their OTS.

Our results on the frequency of changing the airflow rate showed that the subjects did not make many changes. It should be noted that the room temperatures chosen for this study were close to the warmer end of the recommended range in the standards [37,38]. When people feel cool, air movement becomes more perceptible and can be perceived as a draught [54]. If the experiments were done at lower room temperature, adjusting the airflow rate would require more attempts. This situation is likely during the mid-season periods when the room temperature is usually below the upper room temperature setpoint. Another possibility is that the subjects did not prioritize changing the airflow rate, as they already found the thermal condition satisfactory.

There are areas where using LCBCC can be leveraged to reduce the system energy demand. First, the LCBCC system can reach the neutral thermal comfort range at room temperatures as high as 28 °C. Such a level of thermal comfort is usually achieved with total-ventilation systems at lower room temperatures (~22 °C – 24 °C). This raises the possibility of reducing energy for cooling spaces with LCBCC. Second, both ceiling cooling panels and the chilled beam were supplied with high-temperature chilled water (>17 °C). Utilizing the cooling water at such a high temperature unlocks the possibility of using natural sources to provide free cooling instead of using chillers. Ground and nearby bodies of water (lakes and rivers) are examples of such sources [20,21,55,56]. Experiments with breathing thermal manikin will reveal how much the LCB improves inhaled air quality.

4.2. Practical implications

One of the main issues hindering the widespread use of personalized ventilation has been the configuration of air outlets in offices. The proposed localized chilled beam is a ceiling-mounted system, as opposed to desk-mounted personalized ventilation diffusers. LCBs can be used in various office layouts where the occupants do their daily work at a certain place. LCBs can also be customized for heating and cooling applications in office buildings. For instance, the direction and throw pattern of the supply jet can be controlled by the users.

When using the LCBCC systems, particular attention should be paid to flexibility in space layout changes in time. Changes in office layouts pose limitations to both total volume ventilation air distribution as well as LBC systems. With this respect, the localized systems bound to the workstation locations are advantageous, though there is a problem with delivering clean ventilation air. One way to alleviate this issue is using a novel ductless method to bring the ventilation air to the localized ventilation, as suggested in Ref. [41]. Furthermore, various office layouts should consider in the design of the ducts and pipe connections for the LCB systems. Such a comprehensive design offers greater flexibility for any changes in the layout and thus, reduce the cost of retrofitting.

4.3. Limitations

Thermal sensation and PAQ are subjective measures. Individual votes may entail significant differences between individuals' votes since subjective measures are based on personal evaluation of the indoor environment. This study was carried out with a group of 24 subjects in the repeated measures method. Standard deviation in PAQ, OTS acceptability, and air movement acceptability votes varied between +0.2 and +0.4, on the scale of - 1.0 to +1.0. Other human subjective response studies have been performed with either larger or smaller groups of subjects [8,48,57,58]. Given the small standard deviations range, the size of the group in this study seems to be appropriate. To alleviate the limitations of the subjective response approach, analyzing the votes on LTS, OTS, PAQ, etc. on the individual level can be helpful.

5. Conclusions

The objective of this study was to investigate the human response to the non-uniform local thermal environment established by a localized chilled beam combined with chilled ceiling panels (LCBCC). Mixing ventilation combined with chilled ceiling panels (MVCC) was used as the reference system for comparison. The main conclusions of this study are as follows:

- The micro-environment provided by the LCBCC significantly improved the acceptability of the working environment compared to the MVCC. The improvement was higher under the warmer room temperature.
- The thermal sensation votes indicated a significant improvement in the subjects' comfort level with the LCBCC. The thermal environment was rated close to the neutral comfort level at room temperatures as high as 26 °C and 28 °C. The thermal sensation votes indicated a cooler thermal environment at 28 °C with the LCBCC than that with the MVCC at 26 °C. With the MVCC, the overall thermal sensation was "slightly warm" at 26 °C. The thermal sensation votes indicated even a warmer condition when the room temperature increased to 28 °C.
- When using the LCBCC, PAQ was rated close to the "clearly acceptable" level for room temperatures of both 26 °C and 28 °C. When using the LCBCC, PAQ was perceived as more acceptable at a room temperature of 28 °C, compared to a room temperature of 26 °C with the MVCC. PAQ was within the "just acceptable" level with the MVCC for the test conditions.
- The LCB could establish a comfortable micro-environment using supply air with an elevated airspeed. Acceptability of the air movement was rated close to the "clearly acceptable" level for all body parts investigated. In addition, the draught discomfort rate was low, and it affected only 1 of 24 subjects.
- LCB systems are capable of delegating control over the supply airflow rate to individuals. Results on PAQ and acceptability of the work environment indicated the positive influence of using personalized control. In addition, more than 70% of the subjects adjusted the airflow rate at the maximum level and 30% of the subjects preferred a low airflow rate. Results suggest that the subjects used personalized control to adjust their thermal environment more frequently than for a lower room temperature range (~22 °C–24 °C).

CRediT authorship contribution statement

Taha Arghand: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation. **Arsen Melikov:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Zhecho Bolashikov:** Supervision, Funding acquisition, Conceptualization. **Panu Mustakallio:** Writing – review & editing, Funding acquisition, Conceptualization. **Risto Kosonen:** Writing – review & editing, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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