IMPACT OF VENTILATION SYSTEM TYPE ON INDOOR THERMAL ENVIRONMENT AND HUMAN THERMAL COMFORT IN A CEILING COOLING ROOM

by

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A ceiling cooling (CC) system integrated with a mechanical ventilation system is an advanced HVAC system for the modern office building with glass curtain wall. In this paper, considering the influence of heat transfer of external envelope, the indoor thermal environment and human thermal comfort were objectively measured and subjectively evaluated in a CC room with mixing ventilation (MV) or underfloor air distribution (UFAD). Indoor physical parameters and human skin temperatures were measured as the chilled ceiling surface temperature and supply air temperature were 17.1-17.6 °C and 22.2-22.6 °C. Simultaneously, 16 subjects (8 males and 8 females) were selected to subjectively evaluate the thermal environment. The results showed that the difference between mean radiant temperature and air temperature in the occupied zone was 0.8 °C with CC+MV and 1.2 °C with CC+UFAD, and the indoor air velocity was 0.17 m/s with CC+MV and 0.13 m/s with CC+UFAD. In addition, the calculated and measured thermal sensation votes with CC+MV were all slightly less than those with CC+UFAD. Therefore, ventilation system type had a slight impact on the indoor thermal environment and human thermal comfort in the CC room.

Key words: *thermal environment, thermal comfort, ceiling cooling, mixing ventilation, underfloor air distribution*

Introduction

With a CC system, building energy efficiency can be improved by increasing the supply water temperature and chiller evaporation temperature [1-3]. However, the CC system cannot be used alone to control indoor thermal environment due to the lack of mechanical ventilation systems [4, 5], so a CC system is normally combined with a mechanical ventilation system, *e.g.* a MV system, a displacement ventilation system or an UFAD system [6-8]. In the 21$^{\text{th}}$ century, a CC system integrated with a mechanical ventilation system is an advanced HVAC system for the modern office building with glass curtain wall [9, 10].

In the past two decades, more and more researchers began to study the indoor thermal environment and thermal comfort in a room with radiant cooling and mechanical ventilation. Some researchers experimentally studied the indoor thermal environment and thermal comfort

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in a displacement ventilation room with CC or floor cooling [11-14]. Some researchers carried out filed studies of thermal environment and occupant thermal comfort for CC and UFAD or MV [15-17]. Moreover, Tian and Love [18] performed a filed study of occupant thermal comfort and thermal environments with radiant slab cooling.

However, these aforementioned studies did not take into account the influence of the ventilation system type, which clearly affected the indoor air-flow and thermal environment [19-24]. Therefore, the objective of the present work was to study the impact of ventilation system type on the indoor thermal environment and human thermal comfort in a CC room with high external sensible cooling load. The results obtained in this paper may be beneficial for the design and selection of a hybrid system with a CC system and a mechanical ventilation system.

Methods

Test room and condition

The experimental measurements were carried out in a climatic chamber with the dime sions of 3.7 m × 2.8 m × 2.6 m, as shown in fig. 1. The test room was combined with a CC system, a MV system, and an UFAD system [21-24]. The CC system consisted of 11 metal radiant panels with a size of 600 mm × 1200 mm. A typical square diffuser with a size of 600 mm × 600 mm and a typical double shutter with a size of 250 mm × 250 mm were used as the supply terminals for the MV system and the UFAD system, respectively. Electric heating film was used to simulate the heat transfer of external envelopes, and the power was kept at 720 W for simulating the heat transfer of 69.5 W/m^2 [25]. These were four chairs for four participants in any one group during the measurement. Two participants were approximately 2.5 m far away from the electric heating film, and the other two participants were close to the external wall (about 1.0 m from the electric heating film).

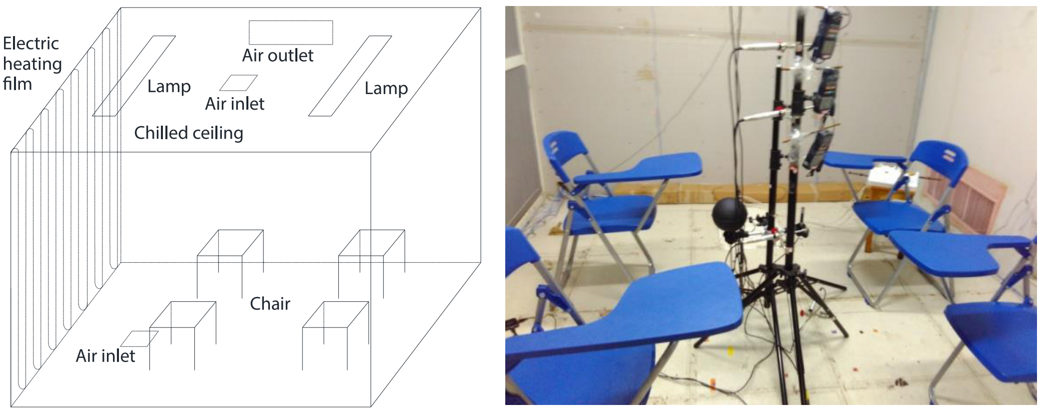

Figure 1. Climate chamber

The test conditions for CC + MV or CC + UFAD were shown in tab. 1, where indoor reference air temperature (at the height of 0.6 m) and supply air temperature were controlled at 26 °C and 22.5 °C by adjusting the supply air-flow rate and the power of electric heater inside the supply vent, respectively. The chilled ceiling surface temperature was kept at 17.5 °C to avoid condensation.

Table 1. Test condition

Test systems	Nominal reference temperature t_a [°C]	Nominal chilled surface temperature t_c [°C]	Nominal supply air temperature t_s [°C]	Heat transfer of external envelope q_{ex} [Wm^{-2}]
CC + MV	26.0	17.5	22.5	69.5
CC + UFAD	26.0	17.5	22.5	69.5

Indoor physical parameters measurements

According to ASHRAE 55 and ISO 7730, indoor thermal environmental parameters include indoor air temperature, air velocity, mean radiant temperature and relative humidity, which were measured and collected using the calibrated instruments, as shown in tab. 2 [26, 27]. These measuring instruments were placed in the middle of the test room and at a height of 0.6 m above the floor, see fig. 1. Besides, indoor CO_2 concentration at three heights in the center of room (0.9 m, 1.1 m, and 1.3 m) were measured by TES 1370. Supply and exhaust air temperature were measured used the calibrated *T*-type thermocouple.

Table 2. Measuring instruments

Measuring parameter	Instruments	Range	Accuracy
Air temperature	Swema 03	10-40 °C	±0.1 °C
Air velocity	Swema 03	0.05-1.0 m/s	±0.03 m/s
Globe temperature	Swema 05	0-50 °C	±0.1 °C
Relative humidity	Swema hygro clip	0-100%	±1%
CO_2 concentration	TES 1370	0-6000 ppm	±50 ppm
Surface temperature	*T*-type thermocouple	10-40 °C	±0.1°C

The calibrated *T*-type thermocouples were also used to measure the surface temperatures of building envelope and the human body. The building envelope surface temperature was measured using the four-point method, which means that four thermocouples were placed in the middle of the two diagonals. Besides, the human body surface temperature was measured using the ten-point method, which means that ten thermocouples were placed at ten locations according to Liu's study, as shown in fig. 2 [28]. Independent two-sample t-tests were used to compare physical parameters measured in the CC room with MV or UFAD.

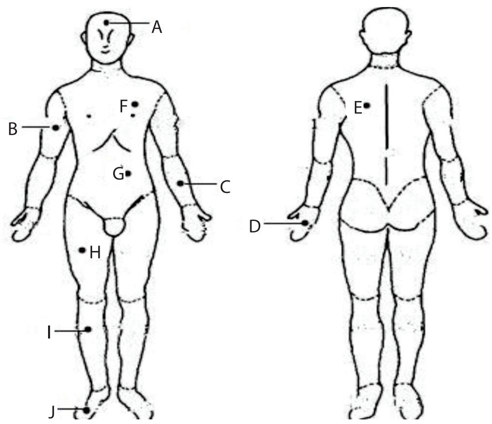

Figure 2. Measuring points of local body skin temperature [28]; *A – forehead, B – upper arm, C – forearm, D – hand, E – back, F – chest, G – belly, H –thigh, I – shank, and J – foot*

Subjective evaluation

Sixteen college students (8 males and 8 females) were selected as participants based on health backgrounds, time availability and background knowledge (not familiar with HVAC systems). These participants were randomly assigned to four groups according to the gender, which means that the gender of four participants in any one group was the same. The details of anthropological data of these participants are shown in tab. 3.

Table 3. Statistic results for 16 subject participants

Gender	Number of subjects	Age [year]	Weight [kg]	Height [cm]	Calculated BMI
Male	8	21.3 ±2.6	60.9 ±5.6	173.4 ±4.3	20.2 ±1.2
Female	8	23.1 ±1.6	51.3 ±2.8	162.8 ±5.1	19.4 ±1.2

During the experiment, the participants were allowed to do light activities (reading, writing, *etc*.) and were required uniformly dressing (about 0.5 clo considering the effect of chair). Each participant completed six questionnaires during 1.5 hours, as shown in fig. 3. At the preparing stage, the participants were asked to stick calibrated *T*-type thermocouples at the ten measuring points on skin surface, as shown in fig. 2. Each participant needed to fill out two subjective questionnaire during the first 0.5 hour, and then continued to fill out one subjective questionnaire every 15 minutes during the 1.0 hour. Hence, each participant should give six votes during 1.5 hours, and the average value of the last three votes during the last 45 minutes was used for analyzing. Meanwhile, indoor physical parameters were also measured and recorded during the last 45 minutes, and the record time interval of the indoor physical parameters measurements was 30 seconds.

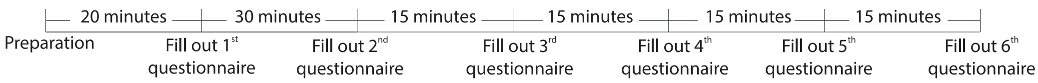

Figure 3. Procedure of subjective evaluations

The questionnaire was designed based on the ISO 10551, and its contents included the votes of overall thermal sensation, thermal comfort, thermal preference, thermal acceptability and other perceptions [29]. The thermal response scale of the subjective questionnaire was shown in tab. 4. The Mann-Whitney U-test was used to examine the differences of thermal responses between CC + MV and CC + UFAD.

Table 4. Scale of participant thermal response

Scale value	Thermal sensation	Thermal comfort	Thermal preference	Preference of air movement	Perceived air quality	Thermal acceptability
–3	Cold	–	Much cooler	–	–	–
–2	Cool	–	Cooler	–	–	–
–1	Slightly cool	–	Slightly cooler	Less air movement	–	–
0	Neutral	Comfortable	Neither warmer nor cooler	No change	Perfectly acceptable	Acceptable
1	Lightly warm	Slightly uncomfortable	Slightly warmer	More air movement	Slightly acceptable	Unacceptable
2	Warm	Uncomfortable	Warmer	–	Slightly unacceptable	–
3	Hot	Very uncomfortable	Much warmer	–	Perfectly unacceptable	–

Calculation formulas

The mean radiant temperature, t_r, and mean skin temperature were calculated using the eqs. (1) and (2) according to ISO 7726 and Liu's study [26, 30]:

$$t_r = \sqrt[4]{\left(t_g + 273.15\right)^4 + \frac{h_c}{\sigma\varepsilon}\left(t_g - t_a\right)} - 273.15 \tag{1}$$

where t_g is the globe temperature, t_a – the average air temperature in the occupied zone, σ – the Stefan-Boltzmann constant, ε – the emissivity of the globe surface, and h_c – the convective heat transfer coefficient:

$$\begin{aligned} t_{sk} &= 0.06t_A + 0.08t_B + 0.06t_C + 0.05t_D + 0.12t_E + \\ &+ 0.12t_F + 0.12t_G + 0.19t_H + 0.13t_I + 0.07t_J \end{aligned} \tag{2}$$

where t_{sk} is the mean skin temperature, t_A – the forehead temperature, t_B – the upper arm temperature, t_C – the forearm temperature, t_D – the hand temperature, t_E – the back temperature, t_F – the chest temperature, t_G – the belly temperature, t_H – the thigh temperature, t_I – the shank temperature, and t_J – the foot temperature.

Results

Indoor physical parameters

Figures 4-7 showed the varied indoor physical parameters as a function of time.

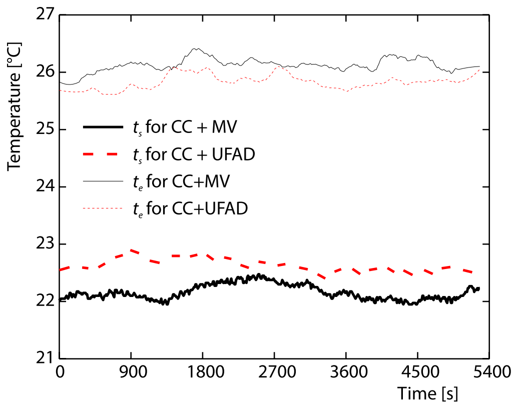

Figure 4. Supply and exhaust air temperature

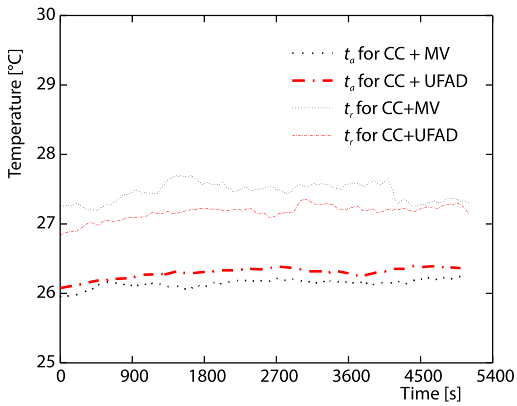

Figure 5. Indoor air temperature and mean radiation temperature

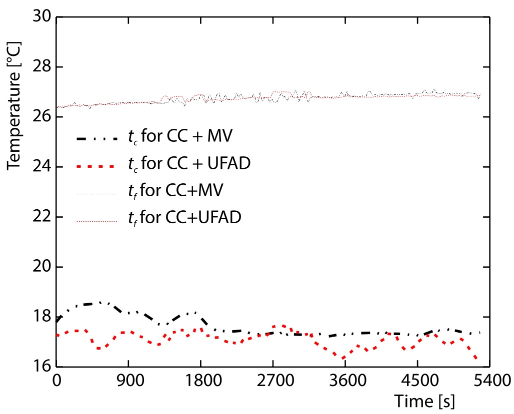

Figure 6. Surface temperature of chilled ceiling and floor and internal wall

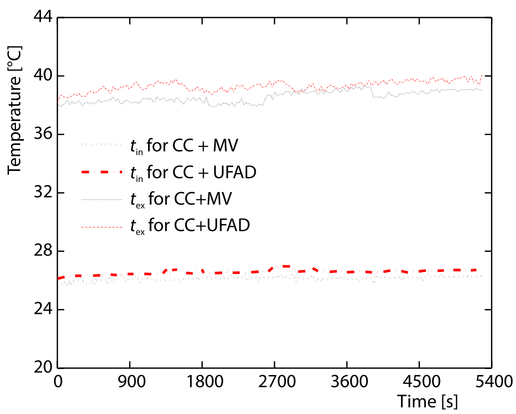

Figure 7. Surface temperature of external wall

The supply and exhaust air temperature, t_s and t_e, with CC + MV and CC + UFAD were continuously investigated, as shown in fig. 4. The average supply/exhaust air temperature were 22.2-26.1 °C with CC + MV and 22.-25.8 °C with CC + UFAD, respectively. Therefore, the average temperature difference between supply air and exhaust air was larger with CC + MV than that with CC + UFAD. This may be due to the smaller air change rate with CC + MV than that with CC + UFAD.

The change of indoor air temperature and mean radiation temperature, t_a and t_r, with CC + MV and CC + UFAD as the time were seen in fig. 5. The average indoor air temperature and mean radiation temperature were 26.2 °C and 27.4 °C with CC + MV and 26.3 °C and 27.1 °C with CC + UFAD. Hence, the average indoor mean radiant temperature was 0.8 °C higher than the average air temperature with CC + MV and 1.2 °C higher than the average air temperature with CC + UFAD. The result was not in agreement with the simulation results from Zhu's study [31]. It may because that in this study the surface temperature of external wall was greatly higher than the indoor air temperature (up to 13 °C) due to the heat transfer of external envelope.

In addition, the average temperature difference between exhaust air and indoor air was 0.1 °C with CC + MV and 0.5 °C with CC + UFAD, (see figs. 4 and 5). It suggested that the exhaust air temperature could represent the indoor air temperature for the control of CC + MV, but it should be careful to use exhaust air temperature instead of indoor air temperature for the control of CC + UFAD.

Figure 6 indicated the varied surface temperatures of chilled ceiling and floor, t_c and t_f, with CC + MV or CC + UFAD as the time changed. The fluctuation of floor surface temperature change curve was slightly small, whereas the fluctuation of chilled ceiling surface temperature change curve was relatively large. This probably because that the surface temperature of chilled ceiling was mainly affected by the supply water temperature, which changed periodically with the operation of the chiller.

The varied surface temperatures of external and internal wall, t_{in} and t_{ex}, with CC + MV or CC + UFAD as the time changed were shown in fig. 7. The fluctuation of the external wall surface temperatures change curve was slightly larger than that of internal wall. This may be due to that the surface temperature of external wall was controlled by the electric heating film, and the slight change of input power resulted in the small fluctuation of surface temperature. Additionally, the chilled ceiling surface temperature with CC + MV was slightly larger than that with CC+UFAD, see fig. 6, whereas the hot external wall surface temperature with CC + MV was slightly smaller than that with CC + UFAD, see fig. 7.

Overall body thermal perceptions

Figures 8(a)-8(f) showed the varied subjective thermal perceptions of overall body as a function of time.

As shown in Figure 8, the subjective thermal perceptions of overall body at the start time were slightly different with those at the end time for both systems, and the participants nearly were adapted to the thermal environment after they stayed in the room for 30 minutes. Hence, occupants will be adapted to the thermal environment with radiant cooling more quickly compared to the thermal environment with traditional convective cooling, and it agreed well with Krajčík's study [14]. Figure 8 also showed that the thermal perception votes in the last 1 hour with CC + MV were almost the same with CC + UFAD, and the votes of thermal sensation and comfort for two systems were all close to 0, which means that participants felt comfortable.

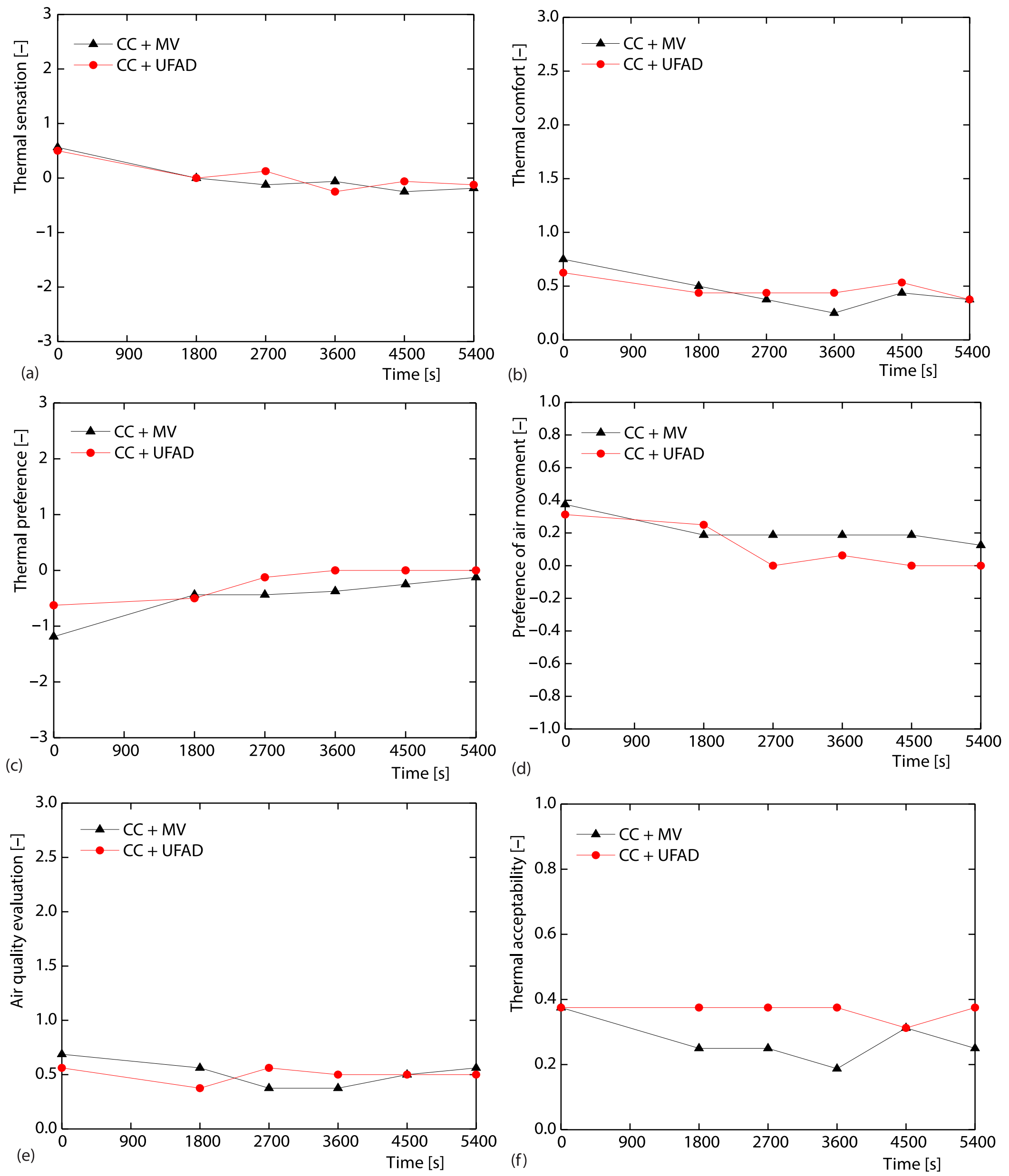

Figure 8. Subjective thermal perceptions of overall body; (a) thermal sensation, (b) thermal comfort, (c) thermal preference, (d) preference of air movement, (e) air quality evaluation, and (f) thermal acceptability

Local body thermal sensation

Figures 9(a)-9(f) showed the subjective thermal sensation of local body as a function of time.

Figure 9 indicated that the thermal sensation votes of local body in the last one hour with CC + MV were almost the same with CC + UFAD. Moreover, the subjective thermal

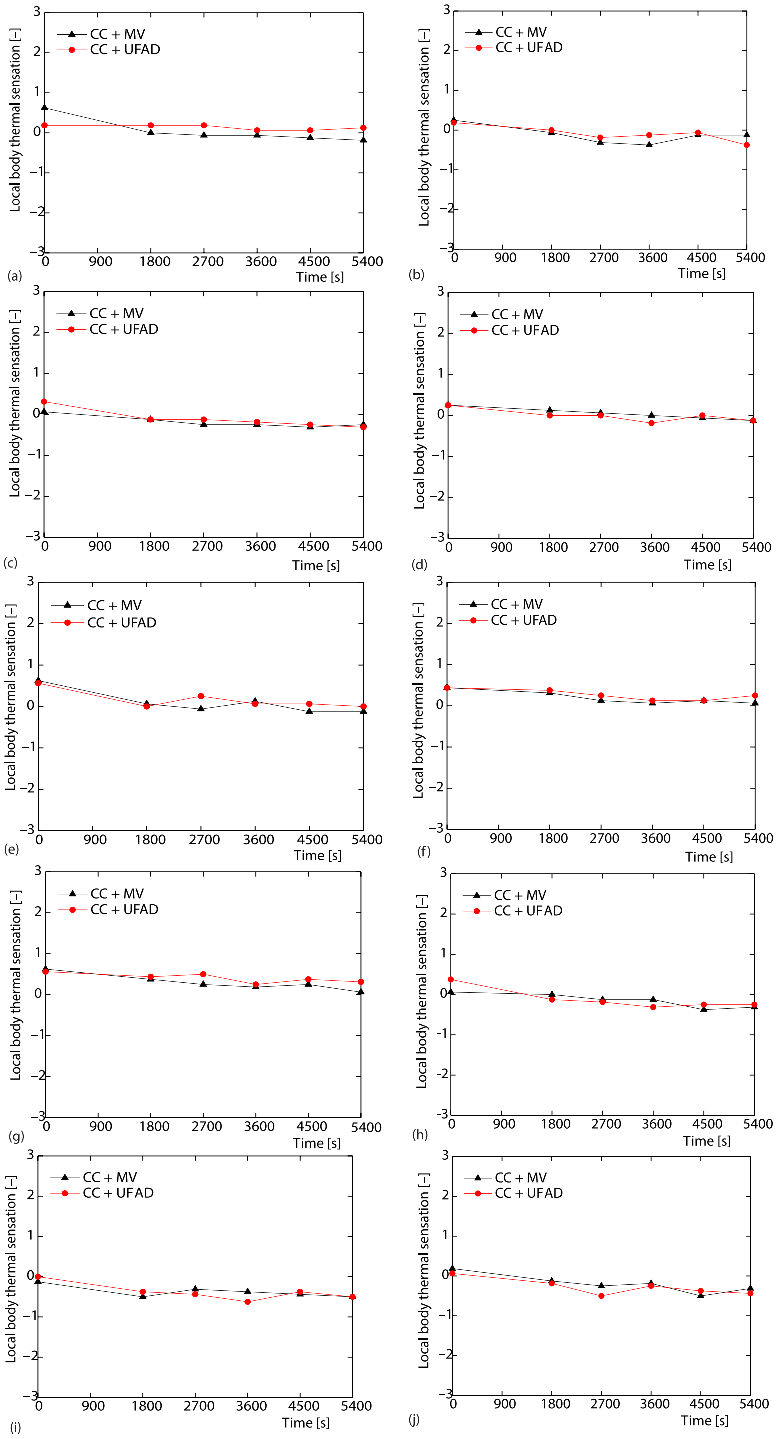

Figure 9. Local body thermal sensations; (a) forehead, (b) upper arm, (c) forearm, (d) hand, (e) back, (f) chest, (g) belly, (h) thigh, (i) shank, and (j) foot

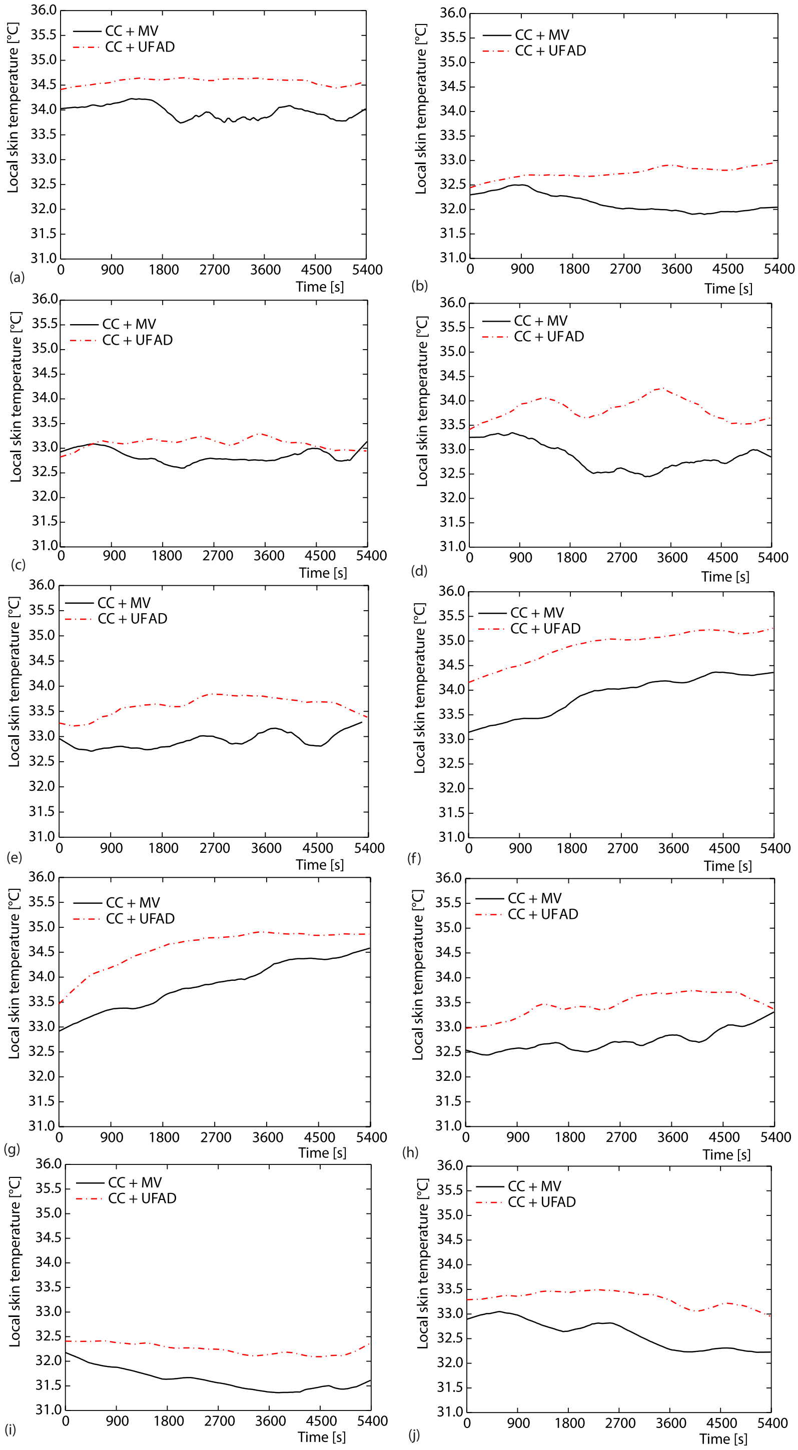

Figure 10. Local body skin temperatures; (a) forehead, (b) upper arm, (c) forearm, (d) hand, (e) back (f) chest, (g) belly, (h) thigh, (i) shank, and (j) foot

sensations of local body at the start time were slightly different with those at the end time with CC + MV or CC + UFAD, and the participants' thermal sensation of local body almost kept at the constant after they have stayed in the room for 30 minutes.

Local body skin temperature

Figures 10(a)-10(f) showed the varied local body skin temperatures as a function of time

As shown in fig. 10, the local body skin temperatures with CC + MV were all slightly smaller than those with CC + UFAD, though indoor operative temperatures were almost the same for the two hybrid systems, see tab. 5. Moreover, most of body skin temperatures can arrive at the stable state after they had stayed in the room for 30 minutes, see figs. 10(a), 10(c)-10(f), and 10(h)-10(i), whereas the changes of the skin temperature of upper arm, belly and foot with CC + MV were nearly unstable during the measurement, figs. 10(b), 10(g), and 10(i). Besides, the fluctuation of hand temperature was clearly larger than other local body skin temperatures, as shown in fig. 10(d).

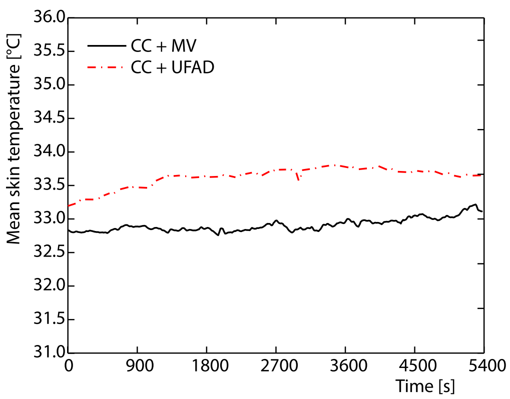

Figure 11. Mean skin temperatures

The mean skin temperature as a function of time was seen in fig. 11, where the mean skin temperature was calculated using the eq. (2). It indicated that the changes of mean skin temperature with CC + MV or CC + UFAD were almost stable after the participants have stayed in the room about 30 minutes. Additionally, the mean skin temperature with CC + MV was clearly less than that with CC + UFAD. This may be due to that the indoor air velocity in the occupied zone with CC+MV was slightly larger than that with CC + UFAD, see tab. 5, and the increased air velocity will result in large heat convection between human body surface and the surrounding environment.

Discussions

Indoor thermal environment

The average values of indoor thermal environmental parameters during the last one hour measurement were shown in tab. 5, where operative temperature is the average value of air temperature and mean radiant temperature.

Table 5. Indoor thermal environmental parameters, Mean±(sd)

Test systems	Air temperature t_a [°C]	Globe temperature t_r [°C]	Air velocity v_a [ms^{-1}]	Relative humidity h_{um} [%]	Mean radiant temperature t_r [°C]	Operative temperature t_o [°C]
CC + MV	26.2 ±0.3	26.8 ±0.4	0.17 ±0.01*	52.0 ±1.8*	27.4 ±0.4	26.8 ±0.3
CC + UFAD	26.3 ±0.2	26.8 ±0.2	0.13 ±0.01*	45.0 ±2.0*	27.1 ±0.2	26.7 ±0.2

* Means significant difference $P < 0.05$

Table 5 indicated that the average values of indoor thermal environmental parameters with CC + MV were almost the same as those with CC + UFAD. The difference between operative temperature and air temperature was 0.6 °C with CC + MV and 0.4 °C with CC + UFAD. It suggests that it should be careful to use indoor air temperature instead of operative temperature for the design and control of CC + MV or CC + UFAD. In addition, despite the air-flow rate with CC + MV was slightly smaller than that with CC + UFAD, the average indoor air velocity with CC + MV was slightly larger than that with CC + UFAD, see tab. 5. This probably because that the indoor air-flows in the room with CC + MV differ from that with CC + UFAD [21-24].

According to ASHRAE 55 and ISO 7730, the participants' metabolic rate was 1.0 met as they were reading and writing. Then the predicted thermal sensation votes (PMV) can be calculated using the indoor thermal environmental parameters, (see tab. 5, as shown in fig. 12.

Figure 12 indicated that the calculated and measured thermal sensation votes with CC + MV were slightly smaller than those with CC + UFAD, though the operative temperatures were almost identical for the two hybrid systems, see tab. 5. This may probably caused by the different mean skin temperature for the two hybrid systems, as shown in fig. 11.

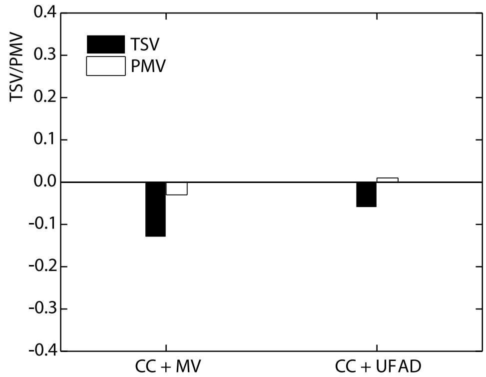

Figure 12. Calculated and measured thermal sensation votes

In addition, the difference between calculated and measured thermal sensation votes were all less than 0.1 scale for the two hybrid systems, which means that the PMV model was still suitable for evaluating the thermal comfort in a CC room with mechanical ventilation. The result agreed very well with Loveday's findings using the laboratory test method [11, 12],whereas it differed from Tian's findings using the field test method [18, 19].This may be due to that the occupant's exposure time in a simulated environment was normally less than 2 hours, whereas it was up to 8 hours in practice [32, 33]. Hence, the occupant's exposure time in a radiant cooling environment should be considered during the design stage of a radiant cooling system combined with a mechanical ventilation system.

Indoor thermal comfort

The comparisons of average overall body thermal perceptions during the last one hour measurement with CC + MV and CC + UFAD were shown in fig. 13.

As shown in fig. 13, the subjective votes of overall body thermal sensation, thermal comfort, thermal preference and thermal acceptability with CC + MV were slightly smaller than those with CC + UFAD. This may be due to the smaller mean skin temperature with CC + MV than that with CC + UFAD, as shown in fig. 11. However, the participants preferred much more air movement with CC + MV, though the indoor air velocity with CC + MV was clearly larger than that with CC + UFAD, see tab. 5. This probably because the indoor relative air humidity with CC + MV was clearly larger than that with CC + UFAD.

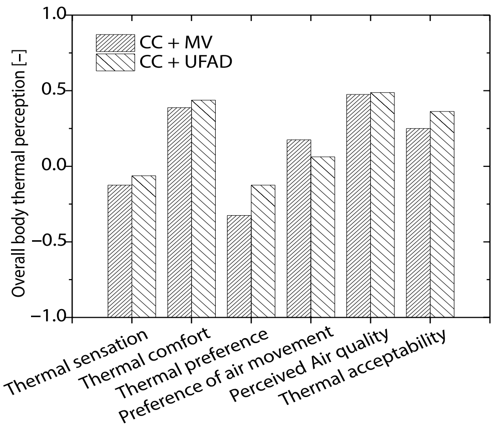

Figure 13. Overall body thermal responses

The comparisons of average local body thermal sensations and skin temperatures during the last one hour measurement with CC + MV and CC + UFAD were shown in figs. 14 and 15. Figure 14 showed that local body thermal sensations of forehead, upper arm, forearm and belly with CC + MV were slightly smaller than those with CC + UFAD, which was in accordance with the local body skin temperature with different hybrid systems in fig. 15. The relations between average local body skin temperature and average local body thermal sensation during the last one hour measurement with CC + MV or CC + UFAD were shown in fig. 16.

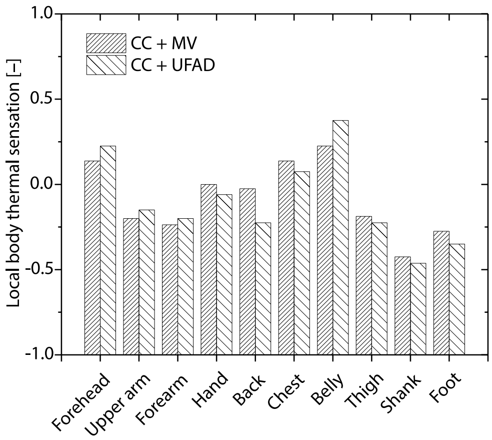

Figure 14. Local body thermal sensations

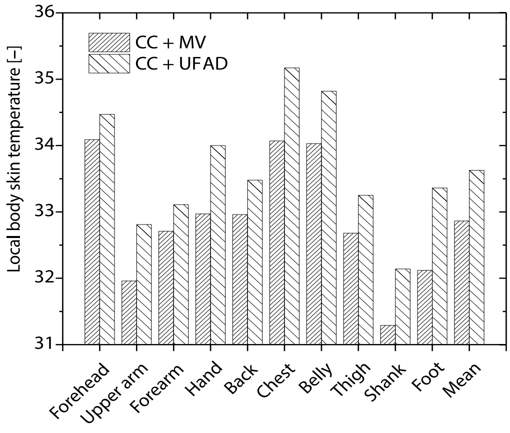

Figure 15. Local body skin temperatures

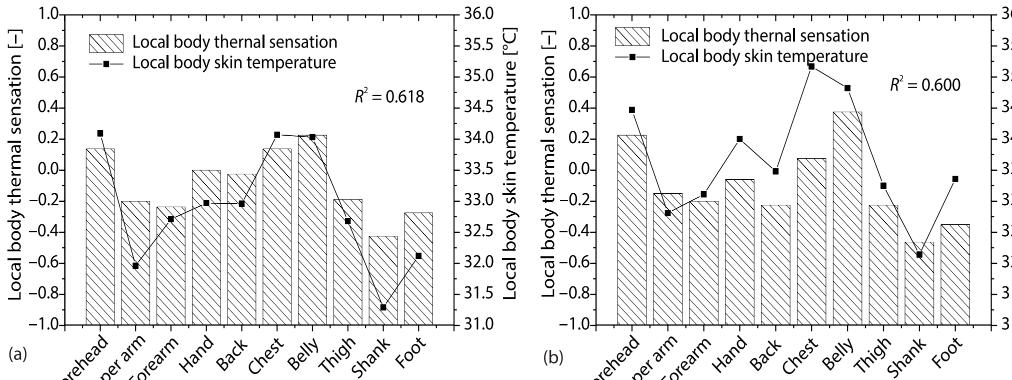

Figure 16. Relations between local body thermal sensation and local body skin temperature; (a) CC + MV and (b) CC + UFAD

Figure 16 indicated that the local body thermal sensation correlated with the local body skin temperature with CC + MV or CC + UFAD, and the according regression coefficients were 0.618 for CC + MV and 0.6 for CC + UFAD. This means that there was a relatively strong relationship between the local body skin temperature and the local body thermal sensation.

In a room with CC and mechanical ventilation, the mean skin temperature or local body skin temperature may be used to represent the overall body thermal sensation or local body thermal sensation. The relationship equations for evaluating the human thermal sensation and thermal comfort will be obtained in the future study.

In this paper, the number of test case was quite small to study the effect of ventilation system type on indoor thermal environment and thermal comfort in a CC room. Although the results and research findings agreed well with the previous studies, many test cases should be needed in the future study to build better confidence in practice.

Conclusions

In this paper, indoor thermal environment and thermal comfort were objectively measured and subjectively evaluated in a CC room with MV or UFAD considering the influence of heat transfer of external envelope, as follows.

- The difference between indoor mean radiant temperature and air temperature and indoor air velocity in the occupied zone with CC + MV were larger than those with CC + UFAD, so the ventilation system type had a slight impact on the indoor thermal environment in the CC room.
- The calculated and measured thermal sensation votes with CC + MV were slightly smaller than those with CC + UFAD, so the ventilation system type had a slight impact on the human thermal sensation in the CC room.
- The local body skin temperatures at all parts with CC + MV were all slightly smaller than those with CC + UFAD (especially for hand, chest and foot), whereas the local body thermal sensation with CC + MV was almost identical with the CC + UFAD.
- Considering the change of local body thermal sensation and skin temperature, it suggests that the occupant's exposure time in a thermal neutral environment with CC and mechanical ventilation should be more than 30 minutes to reach stable state.

Acknowledgment

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