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

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Abstract: 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 ceiling cooling 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°C-17.6°C and 22.2°C-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 0.17m/s with CC+MV and 0.13m/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 ceiling cooling room.

Key words: Thermal environment; Thermal comfort; Ceiling cooling; Mixing ventilation; Underfloor air distribution

1. Introduction

With a ceiling cooling system, building energy efficiency can be improved by increasing the supply water temperature and chiller evaporation temperature[1-3]. However, the ceiling cooling system cannot be used alone to control indoor thermal environment due to the lack of mechanical ventilation systems[4-5]. so a ceiling cooling system is normally combined with a mechanical ventilation system, e.g. a mixing ventilation system, a displacement ventilation system or an underfloor air distribution
In the 21st century, a ceiling cooling system integrated with a mechanical ventilation system is an advanced HVAC system for the modern office building with glass curtain wall\textsuperscript{[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 in a displacement ventilation room with ceiling cooling or floor cooling\textsuperscript{[11-14]}. Some researchers carried out field studies of thermal environment and occupant thermal comfort for ceiling cooling and underfloor air distribution or mixing ventilation\textsuperscript{[15-17]}. Moreover, Tian et al performed a field study of occupant thermal comfort and thermal environments with radiant slab cooling\textsuperscript{[18]}.

However, these studies mentioned above did not take into account the influence of the ventilation system type, which clearly affected the indoor air flow and thermal environment\textsuperscript{[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 ceiling cooling 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 ceiling cooling system and a mechanical ventilation system.

2. Methods

2.1. Test room and condition

The experimental measurements were carried out in a climatic chamber with the dimensions of 3.7m×2.8m×2.6m, as shown in Figure 1. The test room was combined with a ceiling cooling (CC) system, a mixing ventilation (MV) system and an underfloor air distribution (UFAD) system\textsuperscript{[21-24]}. The CC system consisted of 11 metal radiant panels with a size of 600mm×1200mm. A typical square diffuser with a size of 600mm×600mm and a typical double shutter with a size of 250mm×250mm 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 720W for simulating the heat transfer of 69.5W/m\textsuperscript{2} \textsuperscript{[25]}. These were four chairs for four participants in any one group during the measurement. Two participants were approximately 2.5m far away from the electric heating film, and the other two participants were close to the external wall (about 1.0m from the electric heating film).
The test conditions for CC+MV or CC+UFAD were shown in Table 1, where indoor reference air temperature (at the height of 0.6m) 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

<table>
<thead>
<tr>
<th>Test systems</th>
<th>Nominal reference temperature $t_a$ (°C)</th>
<th>Nominal chilled surface temperature $t_c$ (°C)</th>
<th>Nominal supply air temperature $t_s$ (°C)</th>
<th>Heat transfer of external envelope $q_{ex}$ (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC+MV</td>
<td>26.0</td>
<td>17.5</td>
<td>22.5</td>
<td>69.5</td>
</tr>
<tr>
<td>CC+UFAD</td>
<td>26.0</td>
<td>17.5</td>
<td>22.5</td>
<td>69.5</td>
</tr>
</tbody>
</table>

2.2. 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 Table 2. These measuring instruments were placed in the middle of the test room and at a height of 0.6m above the floor (see Figure 1). Besides, indoor CO₂ concentration at three heights in the center of room (0.9m, 1.1m and 1.3m) were measured by TES 1370. Supply and exhaust air temperature were measured used the calibrated Type T thermocouple.

Table 2 Measuring instruments

<table>
<thead>
<tr>
<th>Measuring parameter</th>
<th>Instruments</th>
<th>Range</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>Swema 03</td>
<td>10°C-40°C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td>Air velocity</td>
<td>Swema 03</td>
<td>0.05 m/s -1.0m/s</td>
<td>±0.03 m/s</td>
</tr>
<tr>
<td>Globe temperature</td>
<td>Swema 05</td>
<td>0°C-50°C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>SwemaHygroClip</td>
<td>0-100%</td>
<td>±1%</td>
</tr>
<tr>
<td>CO₂ concentration</td>
<td>TES 1370</td>
<td>0-6000 ppm</td>
<td>±50 ppm</td>
</tr>
</tbody>
</table>
The calibrated Type T 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 Figure 2\(^{(28)}\). Independent two-sample t-tests were used to compare physical parameters measured in the ceiling cooling room with MV or UFAD.

![Figure 2 Measuring points of local body skin temperature\(^{(28)}\)](image)

2.3. 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 4 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 Table 3.

<table>
<thead>
<tr>
<th>Gender</th>
<th>Number of subjects</th>
<th>Age(year)</th>
<th>Weight(kg)</th>
<th>Height(cm)</th>
<th>Calculated BMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
<td>8</td>
<td>21.3±2.6</td>
<td>60.9±5.6</td>
<td>173.4±4.3</td>
<td>20.2±1.2</td>
</tr>
<tr>
<td>Female</td>
<td>8</td>
<td>23.1±1.6</td>
<td>51.3±2.8</td>
<td>162.8±5.1</td>
<td>19.4±1.2</td>
</tr>
</tbody>
</table>

During the experiment, the participants were allowed to do light activities (reading, writing, etc.) and were required uniformly dressing (about 0.5clo considering the effect of chair). Each participant completed 6 questionnaires during 1.5 hours, as shown in Figure 3. At the preparing stage, the
participants were asked to stick calibrated Type T thermocouples at the ten measuring points on skin surface, as shown in Figure 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 min 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 min was used for analyzing. Meanwhile, indoor physical parameters were also measured and recorded during the last 45 min, and the record time interval of the indoor physical parameters measurements was 30 s.

<table>
<thead>
<tr>
<th>Scale Value</th>
<th>Thermal sensation</th>
<th>Thermal comfort</th>
<th>Thermal preference</th>
<th>Preference of air movement</th>
<th>Perceived Air quality</th>
<th>Thermal acceptability</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3</td>
<td>cold</td>
<td>/</td>
<td>much cooler</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>-2</td>
<td>cool</td>
<td>/</td>
<td>cooler</td>
<td>/</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>-1</td>
<td>slightly cool</td>
<td>/</td>
<td>slightly cooler</td>
<td>less air movement</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>0</td>
<td>neutral</td>
<td>comfortable</td>
<td>neither warmer nor cooler</td>
<td>no change</td>
<td>perfectly acceptable</td>
<td>acceptable</td>
</tr>
<tr>
<td>1</td>
<td>slightly warm</td>
<td>slightly uncomfortable</td>
<td>slightly warmer</td>
<td>more air movement</td>
<td>perfectly acceptable</td>
<td>slightly unacceptable</td>
</tr>
<tr>
<td>2</td>
<td>warm</td>
<td>uncomfortable</td>
<td>warmer</td>
<td>/</td>
<td>slightly unacceptable</td>
<td>/</td>
</tr>
<tr>
<td>3</td>
<td>hot</td>
<td>very uncomfortable</td>
<td>much warmer</td>
<td>/</td>
<td>perfectly unacceptable</td>
<td>/</td>
</tr>
</tbody>
</table>
2.4. Calculation formulas

The mean radiant temperature \( t_r \) and mean skin temperature were calculated using the equations (1) and (2) according to ISO 7726 and Liu’s study\(^{[26,30]}\).

\[
tr = \frac{4}{\sigma}\left(\frac{t_g + 273.15}{4}\right)^4 + \frac{h_c}{\varepsilon}\left(t_g - ta\right) - 273.15
\]

(1)

where \( t_g \) is the globe temperature, \( ta \) is the average air temperature in the occupied zone, \( \sigma \) is the Stefan-Boltzmann constant, \( \varepsilon \) is the emissivity of the globe surface and \( h_c \) is the convective heat transfer coefficient.

\[
tsk = 0.06ta + 0.08tb + 0.06tc + 0.05td + 0.12te + 0.12tf + 0.12tg + 0.19th + 0.13tI + 0.07tJ
\]

(2)

where \( tsk \) is the mean skin temperature, \( tA \) is the forehead temperature, \( tb \) is the upper arm temperature, \( tc \) is the forearm temperature, \( td \) is the hand temperature, \( te \) is the back temperature, \( tf \) is the chest temperature, \( tg \) is the belly temperature, \( th \) is the thigh temperature, \( tI \) is the shank temperature and \( tJ \) is the foot temperature.

3. Results

3.1. Indoor physical parameters

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

![Figure 4 Supply and exhaust air temperature](image1)

![Figure 5 Indoor air temperature and mean radiation temperature](image2)
The supply and exhaust air temperature \((t_s\text{ and } t_e)\) with CC+MV and CC+UFAD were continuously investigated, as shown in Figure 4. The average supply / exhaust air temperature were 22.2°C / 26.1°C with CC+MV and 22.6°C / 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 \((t_i\text{ and } t_r)\) with CC+MV and CC+UFAD as the time were seen in Figure 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 Figures 4-5). 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 \((t_c\text{ and } t_f)\) 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 \((t_in\text{ and } t_ex)\) with CC+MV or CC+UFAD as the time changed were shown in Figure 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 Figure 6), whereas the hot external wall surface temperature with CC+MV was slightly smaller than that with CC+UFAD (see Figure 7).

3.2. Overall body thermal perceptions

Figures 8(a) - (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 30min. 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.

3.3. Local body thermal sensation

Figures 9(a) - (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 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 30min.

3.4. Local body skin temperature

Figures 10(a) - (f) showed the varied local body skin temperatures as a function of time. As shown in Figure 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 Table 5). Moreover, most of body skin temperatures can arrive at the stable state after they had stayed in the room for 30min (see Figures 10(a), (c)-(f) and (h)-(i)), whereas the changes of the skin temperature of upper arm, belly and foot with CC+MV were nearly unstable during the measurement (Figures 10 (b), (g) and (i)). Besides, the fluctuation of hand temperature was clearly larger than other local body skin temperatures, as shown in Figure 10(d).
Local skin temperature (℃)

- (c) Forearm
- (d) Hand
- (e) Back
- (f) Chest
- (g) Belly
- (h) Thigh
The mean skin temperature as a function of time was seen in Figure 11, where the mean skin temperature was calculated using the Equation (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 Table 5), and the increased air velocity will result in large heat convection between human body surface and the surrounding environment.

4. Discussions

4.1. Indoor thermal environment

The average values of indoor thermal environmental parameters during the last one hour measurement were shown in Table 5, where operative temperature is the average value of air temperature and mean radiant temperature.
Table 5 Indoor thermal environmental parameters (Mean±(sd))

<table>
<thead>
<tr>
<th>Test systems</th>
<th>Air temperature $t_a(\degree C)$</th>
<th>Globe temperature $t_r(\degree C)$</th>
<th>Air velocity $v_a$(m/s)</th>
<th>Relative humidity $hum(%)$</th>
<th>Mean radiant temperature $t_r(\degree C)$</th>
<th>Operative temperature $t_o(\degree C)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC+MV</td>
<td>26.2±0.3</td>
<td>26.8±0.4</td>
<td>0.17±0.01*</td>
<td>52.0±1.8*</td>
<td>27.4±0.4</td>
<td>26.8±0.3</td>
</tr>
<tr>
<td>CC+UFAD</td>
<td>26.3±0.2</td>
<td>26.8±0.2</td>
<td>0.13±0.01*</td>
<td>45.0±2.0*</td>
<td>27.1±0.2</td>
<td>26.7±0.2</td>
</tr>
</tbody>
</table>

* 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$\degree$C with CC+MV and 0.4$\degree$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 Table 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 1.0met as they were reading and writing. Then the predicted thermal sensation votes (PMV) can be calculated using the indoor thermal environmental parameters (see Table 5), as shown in Figure 12.

![Figure 12 Calculated and measured thermal sensation votes](chart.png)

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 Table 5). This may probably caused by the different mean skin temperature for the two hybrid systems, as shown in Figure 11.

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 ceiling cooling 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\(^\text{32-33}\)\(^\text{1}\). 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.

4.2. 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 Figures 13.

![Overall body thermal responses](image)

**Figure 13 Overall body thermal responses**

As shown in Figure 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 Figure 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 Table 5). This probably because the indoor relative air humidity with CC+MV was clearly larger than that with CC+UFAD.

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 Figures 14-15. 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 Figure 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 Figure 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

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 ceiling cooling 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 ceiling cooling 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.
5. Conclusion

In this paper, indoor thermal environment and thermal comfort were objectively measured and subjectively evaluated in a ceiling cooling (CC) room with mixing ventilation (MV) or underfloor air distribution (UFAD) considering the influence of heat transfer of external envelope, the following conclusions can be drawn:

1) 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 ceiling cooling room.

2) 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 ceiling cooling room.

3) 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.

4) 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 ceiling cooling and mechanical ventilation should be more than 30min to reach stable state.

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