EVALUATION OF THERMAL COMFORT IN CEILING COOLING SYSTEM

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ABSTRACT

The purpose of this study is to clarify the effects of air temperature and ceiling temperature in the cool water circulation type of ceiling cooling system. The experiment was conducted in summer. The subjects (11 young females) were exposed to the following conditions: combinations of air temperatures (27°C, 29°C and 31°C), ceiling temperature (22.7°C, 23.7°C and 24.7°C) in still air and RH 50%. The following results were obtained: the thermal sensation vote was neutral at the mean skin temperature of 34.5°C. Each part of the body was affected by the ceiling temperature, as it gave different skin temperatures. For example, the forehead, the scapula and the abdomen were affected. The thermal comfort vote was rated comfortable even at high environmental temperature and the satisfaction to the ceiling temperature was also valued comfortable in this experiment. The mean skin temperature showed higher thermal neutrality-temperature than that of existing studies for floor and wall radiation heating.

INDEX TERMS

Ceiling radiant cooling, Skin temperature, Thermal comfort vote, Thermal sensation vote, Operative temperature

INTRODUCTION

The floor heating system is understood to be an economical and comfortable heating system...
because it makes use of radiant heat. However, the majority of cooling equipments are conventional air conditioners. But cooling by the conventional air conditioner causes the air distribution of lower temperature around floor and about 3°C higher around ceiling, which is contrary to the typical comfort concept of ‘keeping the head cool and the feet warm’. Moreover the draught caused by direct contact of airflow to human body is also inevitable in case of the conventional one. Therefore, the radiant ceiling cooling is known to be the most comfort system in summer by giving uniform indoor temperature due to its cool radiation from the ceiling. In this regard the radiant ceiling cooling is best suited for home or ward for long term occupation, rooms for the old, library, research lab, and rooms to avoid noise and wind blowing.

Although a large number of studies have been made on air-conditioner cooling in summer conditions, only few attempts have so far been made on cool water circulation radiant cooling system. The purpose of this paper is to investigate the effect of air and ceiling temperature of the ceiling cooling system with cool water circulation unit upon the human body by measuring the skin temperatures and the psychological evaluation.

**METHODS**

The experiment was carried out using a ceiling cooling system [W4m×D2.56m] in climate chambers A[W4.5m×D5m, H2.5m] and B[W3m×D3m, H2.5m] at Nara Womens University. Figure 1 shows the plan of the climate chamber. We installed the ceiling cooling system by the capillary tube panels. Cold water ran through the capillary tubes. The distance between the tubes was 10-30mm. The material of the tubes was polypropylene with Φ 3.4mm. The concerned radiant system with water circulation mates was equipped hanging on the ceiling. The subjects (11 young females) were exposed to the following conditions: combinations of air temperatures (27°C, 29°C and 31°C), ceiling temperature (22.7°C, 23.7°C and 24.7°C) in still air and RH 50% with air velocity less than 0.1 m/s. And the experiment was carried out at

**Table 1. Conditions of Experiment**

<table>
<thead>
<tr>
<th>Environmental Conditions</th>
<th>Ambient Temp. (°C)</th>
<th>Ceiling Temp. (°C)</th>
<th>Water Temp. (°C)</th>
<th>Globe Temp. (°C)</th>
<th>Relative Humidity (%)</th>
<th>Air Velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental Conditions (pretest room)</td>
<td>27</td>
<td>22.7</td>
<td>15</td>
<td>26.4</td>
<td>50</td>
<td>Less than 0.1</td>
</tr>
<tr>
<td>Environmental Conditions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Physical condition and characteristics of subjects**

<table>
<thead>
<tr>
<th>subject</th>
<th>Age (yr)</th>
<th>Height (cm)</th>
<th>Weight (kg)</th>
<th>As (m²)</th>
<th>BMI (kg/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVG</td>
<td>23.1</td>
<td>158.2</td>
<td>49.8</td>
<td>1.50</td>
<td>19.9</td>
</tr>
<tr>
<td>STD</td>
<td>±1.89</td>
<td>±4.70</td>
<td>±4.17</td>
<td>±0.07</td>
<td>±1.60</td>
</tr>
</tbody>
</table>

**Table 3. Time schedule of experiment**

<table>
<thead>
<tr>
<th>Time</th>
<th>Situation</th>
<th>Skin Temp.</th>
<th>Rectal Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>-30min</td>
<td>Pretest room</td>
<td>▶</td>
<td></td>
</tr>
<tr>
<td>0min</td>
<td>Test room</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30min</td>
<td>Exposure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60min</td>
<td>off the chamber</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90min</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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the room temperature as was set during the initial 60 minutes, and during the 30 minutes after so that only the ceiling temperature was controlled while the air temperature control equipment of the climate chamber was put off. Table 1 shows the conditions of experiment.

The air temperature was measured at the center of the experimental room at three different levels (H=0.1, 0.6, 1.1m), and the globe temperatures (Tg, temperature at the floor, at 0.6m and at 1.1m) were measured by a globe thermometer of 15cm in diameter. The ceiling temperatures were measured at 4 points by a thermocouple of diameter 0.1mm. Relative Humidity was measured by an electric motion assmann hygrometer. To determine physiological effects, the skin temperatures of subjects were measured every 5 seconds at 14 points by cc thermocouples (Φ 0.1mm). The skin temperatures were measured and recorded by 30 points hybrid recorder and Φ 0.1mm thermocouple. A rectal temperature was also measured and recorded by the same kind of recorder. The sensor was inserted about 10 cm into the anus of the subject. The weight loss was obtained by weighing the subjects immediately before and after the experiment. The mean skin temperature was calculated by the weighted mean formula at 12 points surface area by Hardy & DuBois. From 30 minutes before the experiment to 60 minutes after, the subject’s psychological evaluation of the whole body and local body was required to describe at the 10 minute interval based on the traditional nine-point scale of thermal sensation votes [-4: very cold through +4: very hot], and seven-point scale of thermal comfort votes [-3: very uncomfortable through +3: very comfortable]. Table 3 shows the time schedule of the experiment.

The subjects were exposed to set conditions while sitting on a chair. The subjects, who were all female, were clothed in summer attire we prepared: T-shirts, short trousers, and their own panties and brassieres. The clothing insulation value was estimated at 0.32 clo. The experiment was done between July and August 2000.

![Figure 2. Changes in skin temperature with air, ceiling temperature](image-url)
RESULTS

Figure 2 shows the changes in skin temperature with the air and the ceiling temperature. Generally skin temperature was ranged from 30°C to 36.5°C. The skin temperature of the trunk parts was stable ranged 34.5°C to 36°C, as it was affected by the air and ceiling temperature. The skin temperature of peripheral parts of the calf and feet had a wide range. The low skin temperature of distribution at Ta=27°C was affected considerably by ceiling temperature. The skin temperature of the parts of the sole and instep dropped about 3°C when comparing the case with Ta=29°C to that of 31°C.

Especially the coefficient of correlation was higher rated at the parts of the scapula and the abdomen. It was affected by the ceiling radiation from above to the trunk parts. And the coefficient of correlation was also higher rated at the parts of the calf and the rectal temperature. This comes from the fact that they were affected by ceiling radiation considerably after putting off air-conditioning, which showed low skin temperature distribution. The mean skin temperature ranged from 34°C to 35°C. The rectal temperature of the subject was stable at the temperature 37.2°C to 37.3°C. Figure 4 shows the relation between upper body skin temperature and thermal sensation vote. The coefficient of correlation was higher valued exceeding 0.9 between the parts of skin temperature of the forehead, the upper chest, the scapula and the thermal sensation vote.

Figure 5 shows the relation among the mean skin temperature, the thermal sensation vote and thermal comfort vote. The thermal sensation vote was rated [-1: slightly cool ~ +1: slightly comfortable]
warm] at the mean skin temperature ranged from 33.5°C ~ 35.5°C. Figure 6 shows the changes in thermal sensation vote with the air and the ceiling temperature.

Figure 5. Changes in thermal sensation vote with air and ceiling temperature

Figure 6. Relation between operative temperature and thermal sensation vote/thermal comfort vote

In case of ceiling radiant cooling, generally, thermal sensation vote was not rated 「hot」 but [-1:slightly cool ~ +1:slightly warm] in spite of high ambient temperature condition. The radiation from the ceiling uniformly affects the whole body. The thermal sensation vote of the all parts valued [-1:slightly cool] except parts of the bottom, Ta=27°C. After putting off the air-conditioning, the parts of the head, shoulder, shin and foot were valued low thermal sensation vote. And in case of Ta=29°C and 31°C, all were valued [0:neutral ~ +1:slightly warm]. All parts of the body were valued same evaluation. In the case of Ta=31°C there was lower value of all body parts than that of Ta=31°C while putting the air-conditioning off. It’s the same evaluation as that of Ta=29°C. Figure 7 shows the relation between operative temperature and thermal sensation/thermal comfort vote. The thermal sensation vote were rated [-1: slightly cool ~ +1: slightly warm] at operative temperature of 26°C ~ 31°C. The levels of comfort were rated ‘comfortable’ at all conditions. Figure 8 shows the relation among operative temperature, satisfaction and thermal sensation from the ceiling temperature.
The thermal sensation from the ceiling temperature was valued ‘neutral’ at all conditions and the satisfaction from the ceiling temperature valued satisfactory in this experiment.

![Figure 7. Relation between operative temperature and satisfaction, thermal sensation from the ceiling temperature](image)

**CONCLUSION**

1) The physiological result was that this system dramatically affects the parts of head and trunk, and uniformly the whole body.

2) The thermal sensation vote was evaluated [-1: slightly cool--+1: slightly warm] at all local body parts, which means that the ceiling radiation affects evenly most of the whole body parts.

3) The thermal comfort vote was rated comfortable even at high environmental temperature.

4) The thermal sensation vote was [-1: slightly cool--+1: slightly warm] at the mean skin temperature ranged from 33.5°C to 35.5°C and neutral at the mean skin temperature 34.5°C. The mean skin temperature showing thermal neutrality was higher than that of existing studies for floor and wall radiation heating.

5) The satisfaction from the ceiling temperature was valued comfortable at all conditions, since the cool radiation from the ceiling to the floor affects the room uniformly. This means that the ceiling radiation cooling system brings the pleasant feeling even under a little higher skin temperature condition and relieves the intensive hot environment.

**REFERENCES**


Handbook of Physiological Science Vol.22. (1987), Physiology of Energy Exchange and Thermoregulation, Igaku-Shoin

Kato, H. et al.(1995): Analyze of the difference of thermal sensation and thermal comfort caused by the different sitting position on floor cooling condition, -The difference between sitting on a chair and sitting on the floor- *Summaries of technical papers of annual meeting architectural of Japan*, Sep.
