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Experimental comparison of thermal comfort during cooling with a fan coil system and radiant floor system at varying space heights

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ABSTRACT

With the development of the economy, architectural space forms and air conditioning systems have become more and more diverse. This paper presents a comparative study on thermal comfort in spaces of varying heights using a fan coil system and a radiant floor system for cooling in the "Comprehensive Experiment Platform of Variable Building Space" located in Tianjin, China. A total of 30 subjects participated the questionnaire survey under 8 different experimental conditions, and the indoor thermal environmental parameters were collected for these two systems at varying space height by instrument monitoring. Results indicated that space height had a significant effect on thermal comfort for both the fan coil system and the radiant floor system. The neutral temperature at space height of 3, 5, 7, and 9 m were 24.8 °C, 24.2 °C, 23.8 °C, and 23.5 °C, respectively. The neutral temperature gradually decreased with height of the ceiling when using a fan coil system, which means that participants had greater requirements for cooling at greater heights. In contrast, the neutral temperature at heights of 3, 5, 7, and 9 m were 23.5 °C, 23.8 °C, 24.1 °C, and 24.5 °C, respectively. The neutral temperature gradually increased when using the floor radiant system with increasing height, indicating that participants had lower requirements for cooling at greater heights. Furthermore, the results of this study demonstrate that the floor radiant system had an advantage over the fan coil system for thermal comfort in a space of greater height.

1. Introduction

Since the introduction of air conditioning technology intended to satisfy the thermal comfort requirements of inhabitants in office buildings, commercial buildings, cinemas, and residential buildings, new types of air conditioning systems have been developed. Researchers have carried out thermal comfort studies on different types of air conditioning systems [1–10]. Air conditioning systems that are widely used at present can be divided into two categories based on their heat transfer mechanism: convective air conditioning systems and radiant air conditioning systems. The pros and cons of these two types of systems for thermal comfort have long been of concern to heating, ventilating, and air conditioning (HVAC) researchers.

1.1. Literature review

Radiant systems have long been used for indoor heating [11]. F.A. Chrenko [12] conducted experimental studies in 1957 on thermal comfort with a radiant floor system in a laboratory measuring 17 × 24 × 14 ft (5.18 × 7.32 × 4.27 m), and determined that the radiant floor system had significant advantage of providing considerable space in the room and having a heating apparatus that is invisible. However, tests of subject foot temperature revealed that radiant floor systems could cause local discomfort. Subsequent research on radiant systems suggested that these systems had many advantages for thermal comfort compared to convective systems. L.Z. Zhang [13] and C. Stetiu [14] suggested that radiant systems could reduce air movement and draft. Furthermore, Zhang concluded that radiant systems provided more homogeneous conditioning in a space by measuring the mean temperature, mean humidity, and maximum relative humidity (RH) with a chilled ceiling system. The same conclusion was obtained by O. Bozkır with field measurements [15]. Results of experiments carried out in an indoor environmental chamber by F. Causone [16] showed that thermal comfort was better with a radiant floor system owing to the highest view factor of the occupants.

Although radiant systems have advantages in terms of thermal comfort, researchers have also discovered their disadvantages. P. O. Fanger and B. W. Olessen [17–19] suggested that a typical feature of the

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Nomenclature

HVAC	Heating, ventilating and air conditioning
CB	Chilled beam
CBR	Chilled beam with radiant panel
CCMV	Chilled ceiling with ceiling installed mixing ventilation
MTVV	Mixing total volume ventilation
ACB	Active chilled beam
TABS	Thermally activated building systems
VAV	Variable air volume
PMV	Predicted mean vote
TSV	Thermal sensation vote
MTSV	Mean thermal sensation vote
ASHP	Air source heat pump
DV	Displacement ventilation

thermal environment with radiant systems was temperature asymmetry, which could cause discomfort for the human body. Both ISO 7730 [20] and ASHRAE 55 [21] indicated that there were limitations of radiant asymmetry with the use of radiant walls, floors, and ceilings. In addition, ISO 7730 and ASHRAE 55 described other features that are unfavorable for human thermal comfort in a radiant-system thermal environment such as floor temperatures that were too low or too high, and a large difference in the air temperature between the head and ankles. In addition, Fanger [22] suggested that drafts caused by air movement could also cause local discomfort.

In addition to analyzing the characteristics of the thermal environment with convective and radiant systems, many researchers have performed comparative studies of thermal comfort with two types of air conditioning systems [23–36].

Q. Jin carried out a human test in a climate chamber during the winter season to study human's thermal sensation. Three low-temperature heating systems were used: a conventional radiator, a ventilation radiator, and floor heating with exhaust ventilation. The results showed that there were no significant differences in thermal sensation or thermal comfort among the three heating systems [23]. However, it could be seen that in the evaluation of thermal comfort of convective and radiant terminals, the results of previous research were inconsistent and sometimes conflicted with each other [24]. P. Mustakallio [25] measured the indoor thermal environment in summer conditions with four different cooling systems: chilled beam (CB), chilled beam with radiant panel (CBR), chilled ceiling with ceiling installed mixed ventilation (CCMV), and overhead mixing total volume ventilation (MTVV). The results indicated that there was little variation in the thermal environment parameters for the four air conditioning systems. To study thermal uniformity with an active chilled beam (ACB) system and conventional air distribution systems, thermal comfort experiments under heating with an air source heat pump, radiator and floor heating were designed by B. Lin [26] at Tsinghua University. The results of occupant thermal comfort questionnaires showed that radiant heating did not provide significantly higher overall thermal satisfaction. K. N. Rheea [27] conducted experiments on a test bed measuring 8.5 m (W) × 11.8 m (L) × 2.7 m (H) and concluded that ACB systems could achieve acceptable thermal uniformity with a lower air flow rate from the air handling unit than with conventional air distribution systems.

In addition to the experimental methods, some researchers have studied thermal comfort for the two types of systems by simulating the parameters of the building environment. G. Salvalai [33] used Energyplus software to simulate an indoor thermal environment with ceiling panels, thermally activated building systems (TABS) and fan coils under cooling conditions, and concluded that the radiation system provided a better thermal environment than the air system. Using Design Builder software, A.A. Chowdhury [35] compared the predicted mean vote (PMV) for a variable air volume (VAV) system and radiant ceiling panels with the same meteorological parameters, and concluded that the radiant system provided a more comfortable thermal environment.

Table 1 summarizes the working conditions, research methods, and results of comparative studies on thermal comfort with convective and radiant systems. In comparing the thermal comfort achieved with convective air conditioning systems and radiant air conditioning systems, the conclusions of these studies are not consistent. It is worth noting that researchers, whether using field research, laboratory studies, or numerical simulations, have largely ignored the impact of the size of the space on the thermal comfort achieved with various types of air conditioning systems. For instance [12], and [25] provide the size of the laboratory and test beds used, respectively, and draw conclusions about thermal comfort for convection and radiant systems for those spatial dimensions. However, it is worth questioning how these conclusions might change if the sizes of the laboratory or test beds were different.

1.2. Objectives

This study aims to investigate the influence of the size of space on thermal comfort with different types of air conditioning systems, and provides a reference for choosing suitable air conditioning systems for buildings of various sizes. To achieve this goal, a comparative experiment was designed using the "Comprehensive Experiment Platform of Variable Building Space" at Tianjin University. Based on existing conditions, a comparative experiment was conducted in cooling conditions with a fan coil system and a radiant floor system in spaces of varying height.

2. Data collection

2.1. Experimental conditions

The Comprehensive Experiment Platform of Variable Building Space

Table 1
Summary of comparative studies with convective and radiant systems.

Author	Condition	Research method	Convective systems	Radiant systems
P. Mustakallio [23]	Cooling	Lab experiment	CB, CBR	MTVV, CCMV
B. Lin [26]	Heating	Field study	ASHP	Floor Heating
K.N. Rheea [27]	Cooling	Lab experiment	Conventional air distribution systems	ACB
S. Schiavon [28]	Cooling	Lab experiment	DV	Chilled ceiling
G. Sastry [29]	Cooling	Field study	VAV	Mixing ventilation
B.W. Olesen [31]	Heating	Lab experiment	Radiant ceiling, radiant floor	Mixing ventilation
R.W. Kulpmann [32]	Cooling	Lab experiment	Radiant ceiling panels with DV	DV
G. Salvalai [33]	Cooling	Building performance simulation	ceiling panels	Fan coil
A.A. Chowdhury [35]	Cooling	Building performance simulation	Radiant ceiling panels	VAV