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Experimentally-determined characteristics of radiant systems for office buildings

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HIGHLIGHTS

- In radiant ceiling panel system, the temperature stratification is modest in cooling mode.
- Air temperature can be used in lieu of operative temperature in controlling radiant systems.
- Use of thin carpet requires the chilled water temperature to be reduced by ~1 K in radiant slab system.

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ABSTRACT

Radiant heating and cooling systems have significant energy-saving potential and are gaining popularity in commercial buildings. The main aim of the experimental study reported here was to characterize the behavior of radiant cooling systems in a typical office environment, including the effect of ceiling fans on stratification, the variation in comfort conditions from perimeter to core, control on operative temperature vs. air temperature and the effect of carpet on cooling capacity. The goal was to limit both the first cost and the perceived risk associated with such systems. Two types of radiant systems, the radiant ceiling panel (RCP) system and the radiant slab (RS) system, were investigated. The experiments were carried out in one of the test cells that constitute the FLEXLAB test facility at the Lawrence Berkeley National Laboratory in March and April 2016. In total, ten test cases (five for RCP and five for RS) were performed, covering a range of operational conditions. In cooling mode, the air temperature stratification is relatively small in the RCP, with a maximum value of 1.6 K. The observed stratification effect was significantly greater in the RS, twice as much as that in the RCP. The maximum increase in dry bulb temperature in the perimeter zone due to solar radiation was 1.2 K for RCP and 0.9 K for RS – too small to have a significant impact on thermal comfort. The use of ceiling fans was able to reduce any excess stratification and provide better indoor comfort, if required. The use of thin carpet requires a 1 K lower supply chilled water temperature to compensate for the added thermal resistance, somewhat reducing the opportunities for water-side free cooling and increasing the risk of condensation. In both systems, the difference between the room operative temperature and the room air temperature is small when the cooling loads are met by the radiant systems. This makes it possible to use the air temperature to control the radiant systems in lieu of the operative temperature, reducing both first cost and maintenance costs.

1. Introduction

Radiant heating and cooling systems are increasing in popularity in both residential and commercial applications [1,2]. One of their advantages is that heat is supplied or extracted through direct radiative heat transfer between the human body and radiant surfaces, as well as indirectly, through convection [3], enabling a radiant cooling system to provide thermal comfort at a higher room air temperature. Radiant cooling systems use higher supply temperatures than mixing ventilation forced air systems and so can make more use of water-side free cooling. Hydronic systems also reduce fan power by more than their increased pump power, which also reduces system energy consumption.

According to ISO 11,855 [4], radiant systems are categorized into three main types: radiant ceiling panels (RCP), embedded surface systems (ESS) and thermally activated building systems (TABS). The TABS and some ESSs have the ability to smooth and shift peak HVAC loads

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Nomenclature

Variables

σ	Stefan-Boltzmann constant (W·m/K^4)
D	diameter of globe temperature sensor (m)
ΔT_a	air temperature difference at two different heights (K)
ε_g	emissivity of the globe temperature sensor
h_c	convective heat transfer coefficient (W/(m^2·K))
Q	chilled water flow rate (L/s)
Q_{solar}	solar irradiance (W/m^2)
RH	relative humidity (%)
T_a	air dry-bulb temperature (°C)
T_g	globe temperature (°C)
T_{op}	operative temperature (°C)
T_r	mean radiant temperature (°C)
$T_{w,sup}$	chilled water supply temperature (°C)
v	air speed (m/s)

Subscripts

a, h	air at h m height
ave	average
oa	outdoor air

and are primarily applied in new constructions, although pipes embedded in a relatively thin topping slab can be installed on the structural slab in some existing building applications [5,6]. RCPs can be installed in suspended ceilings, and so are relatively easy to retrofit in existing buildings, but have no thermal storage capability.

Radiant systems have been widely studied in the literature [7,8]. Rhee and Kim [7] conducted a comprehensive review of the basic and applied research on radiant heating and cooling systems in terms of thermal comfort, energy performance, system configuration and control strategies over the last 50 years. They concluded that radiant heating and cooling systems are fully understood on the basis of building physics and engineering technology, and the future studies should focus on overcoming the limitations and barriers in their application to broader building types and climates. These barriers include the challenge of achieving effective control of radiant slabs due to their long response times. Karmann et al. [8] conducted a critical review of thermal comfort in buildings using radiant systems compared to all-air systems. They concluded that there are indications that radiant systems can provide equal or better comfort than all-air systems.

Recently, some reports in the literature have focused on the differences of sensible zone cooling loads between air system and radiant system [9–12]. Bauman et al. [10] discuss the need for both a new definition of radiant system zone cooling load and the development of a new load calculation procedure.

Table 1 gives a summary of stratification effect values in radiant systems reported in the literature. Causone et al. [13] reported that thermal stratification between 1.1 m and 1.7 m was found with an average value of 0.6 K in cooling mode and 1.1 K to 1.8 K in heating mode. Immanri et al. [14] compared the thermal comfort and energy consumption of a RCP, an air handling unit (AHU) and combined RCP with AHU serving a conference room, concluding that in heating mode the combined system produces smaller stratification of room air temperature, with a max value of 0.9 K between 0.1 m and 1.1 m, and is able to generate a more comfortable environment than the AHU running alone. Song et al. [15] examined a RS system integrated with a dedicated outside air system (DOAS) with outdoor reset control. An air temperature stratification of approximately 2.0 K between 0.1 m and 1.1 m was observed when the indoor temperature was regulated at 26 °C. Causone et al. [16] conducted laboratory experiments showing that under a typical European office room layout, RS system combined with displacement ventilation (DV) could create modest air stratification (0.4–0.9 K) between head and ankles, but may cause thermal discomfort when running in cooling mode with a maximum difference value of 6.6 K. Schiavon et al. [17] investigated the effect of the ratio of cooling load removed by a RCP integrated with DV, and concluded that the air stratification effect was highly influenced by the portion of cooling load removed by the RCP and the surface temperature of the cooled radiant panel. Zhao et al. [18] proposed a radiant-capillary-terminal (RCT) floor heating system with solar phase change thermal storage (SPCTS). The vertical temperature differences from 0.1 m to 1.1 m above the floor ranged from 0.6 K to 0.9 K in their study. However, some of the above mentioned experiments [13,17] were conducted in test chambers that have no windows and so the impact of the solar heat gains was not considered in their studies.

The temperature of a radiantly-conditioned space is generally evaluated in terms of the operative temperature, which is defined as the weighted average of air temperature and mean radiant temperature and is often used as an index to evaluate thermal comfort and size radiant heating and cooling systems [19]. ISO 7726 [20] lists three methods for measuring the mean radiant temperature, i.e., (1) using black-globe thermometer, which is the most commonly used one [21], (2) using two sphere radiometer, (3) using constant air temperature sensor. For the HVAC (heating, ventilation and air-conditioning) applications, both ISO [20] and ASHRAE [21] recommend a black-globe thermometer consists of a hollow sphere of 150 mm diameter, coated in flat black paint with a thermocouple or thermometer bulb at its center, with a response time of 20–30 min. However, because of its size and the long-time constant characteristic, it is impractical to use it in the control of HVAC systems [22]. It is possible to use a smaller globe, thought the change in size increases the weighting of the air temperature relative to the radiant temperature; however, it has recently been suggested [23] that the difference between the air temperature and the operative temperature in radiantly-cooled commercial spaces may be small enough to allow the air temperature to be used as a proxy for the operative temperature.

Table 1
Summary of ranges of thermal stratification of radiant cooling systems in previous studies.

Reference	System	Test facility	Floor area (m^2)	Height range (m)	Temperature stratification (K)
Causone et al. [13]	RCP	Underground test chamber	11.6	1.1–1.7	0.6 (Cooling mode) 1.1–1.8 (Heating mode)
Immanri et al. [14]	RCP + AHU	Small office meeting room	33.0	0.1–1.1	0.9 (Heating mode)
Song et al. [15]	RS + DOAS	Thermally insulated test cell	5.8	0.1–1.1	2.0 (Cooling mode)
Causone et al. [16]	RS + DV	Thermally insulated test cell	16.8	0.1–1.1	3.2–6.6 (Cooling mode) 0.4–0.9 (Heating mode)
Schiavon et al. [17]	RCP + DV	Test chamber within a large conditioned test hall	18.2	0.1–1.1	1.5 or higher when all radiant ceiling surface temperatures are 18 °C or higher (Cooling mode)
Zhao et al. [18]	RCT + SPCTS	One room of a residential house	11.8	0.1–1.1	0.6–0.9 (heating mode)