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Experimental study on the characteristics of non-steady state radiation heat transfer in the room with concrete ceiling radiant cooling panels

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A B S T R A C T

The dominant heat transfer between ceiling radiant cooling panels (CRCP) and indoor environment is the combined heat transfer of thermal radiation and natural convection. Currently, researchers usually discussed indoor radiation heat transfer under steady state conditions rather than non-steady state conditions. In this study, an experimental chamber was built to investigate the indoor parameter variations during the CRCP start-up process in summer, and a mathematical model was also established for further analysis of non-steady state radiation heat transfer. There was a concrete ceiling radiant cooling panel (C-CRCP) equipped in the chamber, and the panel was a concrete slab with pipes embedded in it. The experimental results showed that the temperature of the ceiling surface suddenly dropped after the C-CRCP started up, but the temperatures of the other inner surfaces and the indoor air decreased gradually with a similar trend. The radiant heat flux of the ceiling reached a trough rapidly, and then increased back to steady status step by step. Moreover, it took 7–9 h to nearly get steady status after the C-CRCP started up because of the thermal inertia and the thermal storage of concrete slab. The ratio of radiation heat transfer in the total heat transfer of the ceiling ranged from 40% to 60%. Based on the useful experimental data obtained in this C-CRCP system, a reliable start-up control strategy was also proposed in this paper.

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1. Introduction

Much attention has been devoted to the ceiling radiant cooling panels (CRCP) systems recently because of the advantages such as thermal comfort and energy saving. Concrete ceiling radiant cooling panel (C-CRCP) with embedded pipes is one type of the terminal devices in CRCP systems. Higher temperature chilled water (12–16 °C) is supplied to the pipes to make the ceiling a cold radiating surface, which has heat transfer with the indoor environment via thermal radiation and natural convection. CRCP technique derived from Europe, and a number of research topics have been performed. The heat transfer mechanism between the ceiling and the indoor space was discussed by several investigators around the world.

Mumma and his team [1–7] had done a lot of research work in the field of CRCP systems combined with ventilation devices from different aspects, such as the system concept, heat transfer characteristic, cooling capacity, condensation, design parameters, economic cost, thermal comfort, energy conservation and control strategy. Ardehali et al. [8] analyzed the characteristics of radiation heat transfer (based on steady state net-radiation method) [9] by modeling the heat transfer mechanisms of radiant panels with the consideration of the occupant in the thermal zone. Radiative and convective heat transfer coefficients at the ceiling were investigated by Karadag [10,11], who numerically simulated the convection heat transfer and theoretically calculated the radiation heat transfer of different room dimensions, thermal conditions and surface emissivities. The heat transfer coefficients between the radiant ceiling and the room of office or residential buildings were experimentally evaluated by Causone et al. [12]. Rahimi et al. [13] employed a model with steady state net-radiation method to compute the radiation heat transfer from the heated ceiling surface to the other inner surfaces, and obtained the ratio of radiation and natural convection. Fonseca and his team [14–18] considered radiant panels as dynamic heat exchangers to model the radiant ceiling panels in heating and cooling modes, and evaluated the

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Nomenclature

A	area (m^2)
P	perimeter (m)
L	characteristic length (m)
T	thermodynamic temperature (K)
q	heat flux (W m^{-2})
h	convective heat transfer coefficient (W m^{-2} K^{-1})
g	local gravity acceleration (m s^{-2})
λ	thermal conductivity (W m^{-1} K^{-1})
η	electric-thermal radiant conversion efficiency
φ	view factor
ε	emissivity
σ	Stefan–Boltzmann Constant ($\sigma = 5.67$ W m^{-2} K^{-4})
δ	Kronecker function
ν	kinematic viscosity (m^2 s^{-1})
Nu	Nusselt number
Gr	Grashof number
Pr	Prandlt number
Δx	absolute error
x_{cal}	calculated value
x_{mea}	measured value
E_R	relative error (%)

Subscript

par	parallel
ver	vertical
rad	thermal radiation
con	natural convection
wall	wall
air	air
k, n, i	number of the surfaces
M	qualitative
τ	time step

behavior of the radiant ceiling system and the interactions with the environment. Cooling capacity and heat transfer coefficients under steady state conditions of a cooled radiant ceiling with capillary tubes were experimentally studied by Manuel et al. [19]. Carli et al. [20] presented a numerical model to simulate the dynamic behavior of water embedded heating and cooling systems and predicted the real room conditions. Tian and his team [21–23] explored the actual cooling performance of CRCP without mechanical ventilation and established heat transfer models under steady state conditions to simulate the cooling capacity of radiant cooling terminals with different heat sources. Zhang et al. [24] experimentally studied the cooling and heating performances of the suspended metal ceiling radiant panel with inclined aluminum fins and determined the convection and radiation heat transfer coefficient of the panel in test rooms. Feng et al. [25] experimentally investigated the dynamic heat transfer differences between a radiant system and an air system, and how such differences influenced the cooling load calculation methods for radiant systems. The results showed that the instantaneous cooling rates of the radiant system were 18–21% higher than those of the air system. Le Dreau and Heiselberg [26] performed steady-state simulations of a typical office room equipped with four types of terminals (active chilled beam, radiant floor, wall and ceiling), and conducted a sensitivity analysis to determine which parameters mostly affected the thermal performance. Yin et al. [27] focused on the heat transfer performance and moisture condensation phenomenon of three kind of capillary radiant cooling panels in a constant temperature and humidity environment chamber. They found that heat transfer performance of the radiant panels was improved with the increase of the flow velocity of the chilled water and the temperature difference between the chilled water and the ambient thermal environment. The theoretical derivation process of the dynamic removal thermal loads of radiant cooling ceilings was provided by Arcuri et al. [28], in order to evaluate thermal power removed by convection, infrared radiation and direct absorption of solar radiation incident on ceiling surface (called direct water load) correctly. Li and his team [29–31] studied non-steady state heat transfer between the ceiling radiant cooling panels and the indoor environment and cooling characteristics inside the concrete ceiling radiant cooling panels. Besides, occupant local thermal sensation in the offices with cooling ceiling was also investigated.

Through literature review, a lot of work has been done on the steady state radiation heat transfer between the CRCP and the indoor space, and the type of the CRCP involved was almost metal radiant panel which has small thermal inertia. However, the indoor thermal radiation environment is actually influenced by a variety of factors that may break the steady state. For instance, the heat gain of building envelope keeps changing with the variations of exterior disturbances such as sunlight and outdoor ambient air temperature, thus the inner surface temperatures of the walls are always changing. Thermal environment may also change because of the start-stop of CRCP and indoor heat sources or personnel entering and leaving. Few studies related to non-steady state radiation heat transfer in the room with C-CRCP which has large thermal storage have been published. This paper aims to study the characteristics of indoor non-steady state radiation heat transfer during the C-CRCP start-up process. We built an experimental chamber and emphatically analyzed the temperature variations of the surfaces and the air in the chamber, the heat flux variations of radiation heat transfer, and the proportion of thermal radiation in the total heat transfer of the C-CRCP. Based on the useful experimental data obtained, a reliable starting control strategy was also proposed in this paper.

2. Experiment descriptions

2.1. Experimental chamber

The experimental chamber was built in a large room where the environment was stable. The dimensions of the chamber were 2000 mm × 2000 mm × 2820 mm (length × width × height). The walls were constructed of autoclaved aerated concrete blocks with thin plastering, while the floor and the roof were covered with extruded polystyrene (XPS) insulation boards and sealed well. The interior space of the chamber was separated by the C-CRCP, where the upper space was set up to simulate the upper storey of buildings while the lower space was the test space. The dimensions of the test space were 1600 mm × 1600 mm × 1500 mm (length × width × height). There was an inspection window on the west wall, which was sealed by a XPS insulation board (thickness: 100 mm) during the experimental process to guarantee air tightness. The real picture and the schematic diagram of the experimental chamber are shown in Fig. 1.

The thermal conductivities λ of those building materials are as follows [32]:

- Autoclaved aerated concrete block: 0.14 W m^{-1} K^{-1}
- Extruded polystyrene (XPS) insulation board: 0.028 W m^{-1} K^{-1}

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