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Thermal performance of a suspended ceiling fin heat transfer panel with drain pan

Wenhao Zhao[a], Yingning Hu[a,b,*], Yan Wang[a,b], Wenqi Qin[b]

[a] School of Mechanical Engineering, Guangxi University, Nanning, 530004, China
[b] Key Laboratory of Disaster Prevention and Structural Safety of China Ministry of Education, School of Civil Engineering and Architecture, Guangxi University, Nanning, 530004, China

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ABSTRACT

Radiant air conditioning systems provide better comfort and energy efficiency than air conditioning systems based on forced convection. In order to prevent condensation, the surface temperature of the radiant heat transfer component in conventional radiant air conditioning must be maintained above the dew point temperature, resulting in insufficient cooling capacity. In this paper, a new type of suspended ceiling fin heat transfer panel with a drain pan is proposed to achieve a large temperature difference for the cooling/heating supply. This panel has the characteristics of large heat flux per unit area, sufficient cooling capacity, and simplified heat exchange system. The research results show that the heat flux of the fin heat transfer panel accounts for 90%. In a comparison of the suspended ceiling radiant panels of different structures, the suspended ceiling fin heat transfer panel may be used with a refrigerant with a lower temperature relative to the other two structures and has great potential to improve heat flux, which can reduce the installation area of indoor radiant panels. Finally, the structure of the fin heat transfer panel was optimised. When the fin spacing of the fin heat transfer panel was 5.2 mm, the cooling/heating capacity of the fins was improved by a factor of 1.5 compared to the panel with the original spacing of 1.8 mm, and the metal material required was reduced to approximately 33% of the total. These results serve as a theoretical and practical reference for the study of such air conditioning systems.

1. Introduction

Building energy consumption, accounting for 20%–40% of the national energy consumption in both developed and developing countries, has been an important concern of the world [1]. Nevertheless, the energy consumed by building sector keeps increasing with the improving living quality and growing population [2,3]. Global warming and urban heat island effect also increase ambient temperature and energy consumption of buildings with cooling requirements [4,5]. Apart from the traditional strategies of natural ventilation [6,7], air conditioning systems have been increasingly acknowledged as an essential approach to regulating indoor temperature and indoor air quality in modern households. This, however, leads to a high proportion of energy consumption, approximately 30%–60% of the total energy consumption of buildings [8,9]. Therefore, there is a clear need to reduce energy consumption while improving comfort. At present, the main types of air conditioning terminals include fan-coil units, all-air system terminals (for example diffuser unit), and radiant terminals. Although the fan coil units and the all-air terminals are widely installed in refrigeration systems [10,11], there are several problems associated with these systems such as excessive wind speed and poor comfort [12,13]. Karmann et al. [14] conducted a literature review of a performance comparison between the all-air systems and the radiation systems, and analysed three primary aspects: building performance simulation (BPS), physical measurement, and human subjective testing. It was concluded that the radiant heating and cooling systems provided better comfort than the all-air systems. Imanari et al. [15] compared radiant ceiling systems to conventional air conditioning systems in terms of thermal comfort. The results showed that the radiant ceiling system produced a smaller vertical temperature change and a more comfortable environment than conventional systems. Khan et al. [16] investigated the energy-saving potential of a commercial building with a radiant cooling system combined with a dedicated outdoor air system in India. By comparing the energy consumption, the radiation system was determined to be 17.5% more efficient than the conventional all-air system. Dreau et al. [17] analysed the performance of convective terminals and radiant terminals, and determined the parameters that affected performance using sensitivity analysis. Compared to the convective terminals, the

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[*] Corresponding author. School of Mechanical Engineering, Guangxi University, Nanning, 530004, China.
E-mail address: yingninghugxu@126.com (Y. Hu).

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Nomenclature

S	fin spacing (mm)
H	fin height (mm)
Nu	Nusselt number
Ra	Rayleigh number
g	acceleration of gravity (m/s^2)
α	air thermal diffusivity (m^2/s)
ν	kinematic viscosity (m/s^2)
β	thermal expansion coefficient (1/K)
ε	emissivity
$F_{\varepsilon s-j}$	radiation interchange factor
F_{s-j}	view factor between cooled radiant surface and j-surface
A	area (m^2)
k	air thermal conductivity ($W/(m \cdot K)$)
L	feature length based on geometry (mm)
P	plate circumference (mm)
$AUST$	average unheated surface temperature (°C)
T_w	refrigerant temperature (°C)
T_r	average fin temperature (°C)
T_a	air temperature at 1.1 m (°C)
T_s	bottom drain pan surface temperature (°C)
h_t	radiative heat transfer coefficient ($W/(m^2 \cdot K)$)
h_c	convective heat transfer coefficient ($W/(m^2 \cdot K)$)
q	heat flux density (W/m^2)

Subscripts

c	convective
r	radiant
t	top of the radiant panel
b	bottom of radiant panel
tot	total
j	j-surface

radiant terminals were able to achieve a more uniform temperature distribution. In summary, previous studies have revealed that radiant air conditioning systems have superior energy-saving potential and can achieve a higher level of comfort compared to fan-coil terminals and all-air systems.

However, the main problem with radiant terminals is related to condensation and an insufficient cooling capacity, especially in hot and humid climates. It is typically difficult to simultaneously address both of these issues. In order to prevent condensation, the surface temperature of the radiant heat transfer component should be higher than the indoor dew point temperature, which limits the cooling capacity of the radiant panel. Therefore, numerous investigations have been performed with the objective of improving the terminal structure of radiant conditioning terminals, to reduce condensation risk and improve cooling capacity.

- To solve the condensation problem, the surface temperature of the radiant panel structure is maintained above the dew point temperature by means of a buffer layer or reasonable control of the operating parameters. For example, Ning et al. [18] studied the temperature distribution and condensation of a cooling radiant ceiling panel with an air layer inside and optimised the radiating structure with computational fluid dynamics (CFD). The research results indicated that an air layer can improve the cooling capacity and also reduce the risk of condensation. Yuan et al. [19] investigated the concept of a safe operating area based on the intrinsic correlation between the total heat flux of the radiation system and the surface temperature of the panel. Furthermore, a simplified panel surface temperature model was developed and based on which the condensation free control logic was proposed. The radiant terminal condensation problem can also be solved by using a forced convection terminal to reduce the condensation risk, and this terminal can also handle the indoor latent heat load. For example, Kim and Leibundgut [20,21] proposed a new radiant air system which combined radiant a cooling panel system and an airbox convector unit, and developed an advanced cooling and dehumidification strategy. This novel system not only reduced moisture condensation risk, but also contributed to system energy saving capacity. Song et al. [22] showed that the combination of the floor radiant cooling system and the dehumidification ventilation system can effectively address the condensation problem of the radiant panels in the hot and humid seasons in Korea. In this investigation, the temperature of the chilled water supplied to the radiant floor was controlled and an indoor temperature feedback control was used to respond to internal load changes. In summary, the present study shows that the anti-condensation approach mainly relies on indoor air circulation to remove indoor humid air, that is, through the process of dehumidification fresh air or indoor condensation dehumidification forces the convection heat exchanger to achieve deep dehumidification indoors. Another approach is to enhance the temperature of the cooling medium, however, this results in the additional problem of insufficient cooling.
- The cooling capacity mainly depends on the temperature difference between the surface of the radiant panel and the indoor environment, and the heat exchange area of the radiant panel. However, the larger the temperature difference, the more likely the condensation surface will form dew condensation. Therefore, most of the current methods address the challenges related to the cooling capacity of the radiant panel primarily by increasing the heat exchange area and heat transfer coefficient of the radiant panel. Jeong et al. [23] established a mathematical model for heat transfer of suspended ceiling metal radiant panels. The upper and lower parts of the structure can exchange heat with the indoor environment, and the heat exchange area is increased relative to the buried radiant panel. Estimated the cooling capacity and analysed the influence of different structural parameters on the cooling capacity. Zhang et al. [24] investigated a new type of suspended metal ceiling radiant panel with inclined aluminium fins. In typical office rooms, the cooling capacity of inclined fins is approximately 19% greater than for suspended panels. Li et al. [25] estimated the cooling capacity of the radiant panel with an orifice plate. It was observed that opening the radiant panel increased the convective heat transfer coefficient. Finally, the operating performance of the system and the comfort of the indoor environment were analysed. Yu et al. [26] established a heat transfer model for serpentine metal panels, and used the model to optimise parameters such as water temperature, pipe spacing, and panel thickness, to improve the cooling capacity of metal panels. Singh et al. [27] studied the influence of the contact area between the fins of the module radiation panel and the copper tubing on the heat transfer coefficient. The simulation was performed using COMSOL 5.1. The results showed that the larger the contact area, the larger the heat transfer coefficient. It can be seen from the aforementioned that due to insufficient cooling capacity per unit area, it is necessary to increase the installation area of the radiant panel. In the case that the ceiling surface cannot satisfy the cold load demand, it is often necessary to install a radiant heat transfer device on the wall surface, which affects the use of the indoor space. By adjusting the installation method, the heat exchange amount can be effectively increased. However, due to the required control of the dew point temperature, the problem of the cooling demand and the risk of condensation cannot be fundamentally addressed.