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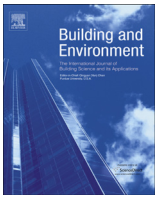

# Cooling capacity improvement for a radiant ceiling panel with uniform surface temperature distribution

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ABSTRACT

Cooling radiant ceiling panel (CRCP) system has the potential of energy saving, improved thermal comfort as well as good indoor environment. We found that a CRCP with thin air layer has uniform surface temperature distribution, which is beneficial for condensation control in hot and humid areas of China. However, with this structure, cooling capacity of the CRCP is decreased. We used surface temperature distribution as well as cooling capacity to have a comprehensive evaluation of the CRCP. We established computational fluent dynamics (CFD) model to calculate the surface temperature distribution and cooling capacity for the CRCP, which is verified by experimental data. Three improved CRCP types with thin air layer are proposed to improve the cooling capacity. The cooling capacities are increased by 43–46% compared to the original CRCP; while uniform surface temperature distribution is retained. We also found the cooling capacities of improved CRCPs are larger than general CRCP type, when maintaining the same minimum surface temperature for condensation control. Meanwhile, this requires lower chilled water temperature and better insulation for pipes, manifolds and fittings than general CRCP type.

## 1. Introduction

Radiant cooling and heating systems are gaining popularity and the application of these systems has increased in recent years, due to their energy saving potential, improved thermal comfort as well as good indoor air quality compared to conventional all-air systems [1–4]. Among them, cooling radiant ceiling panel (CRCP) is one representative type, which is panel with integrated pipes suspended under the ceiling [5]. Compared to the radiant system types like pipes embedded in the surface layer or concrete layer of the building structure, CRCP provides extensive flexibility for zoning and control and responds faster, which can be used both in the new and retrofit buildings. In addition, panel cooling have 16 advantages according to the general evaluation section in ASHRAE Handbook [6].

However, radiant panel is faced with condensation problem (mainly refers to panel surface condensation) when the technology was introduced to hot and humid areas of China. Hu and Niu [7] wrote a review on the application of radiant cooling system in China; they found that condensation is one of the problems that limit the application of radiant cooling in hot and humid areas of China. In addition, some CRCP introduced from European countries are faced with serious condensation problems during the commissioning and operating phases in Shanghai [8].

Currently, there are a lot of studies on solving the condensation problem for CRCP. Design standards and guidebooks recommend using higher chilled water temperature to prevent condensation [9,10]. However, the cooling capacity is decreased with the increase of chilled water temperature. Wongkee et al. [11] found that cooling capacity of one CRCP type is limited to 30 $W/m^2$, due to the hot weather of Thailand in April and the need to avoid condensation. On the other hand, Mumma [12] recommended using parallel dedicated outdoor air systems (DOAS) in place to decouple sensible and latent loads. It's indicated that condensation can be avoided so long as the DOAS and panel loop temperature controls are operated correctly. In addition, to investigate the influencing factors of condensation, Yin et al. [13] used high speed camera to take the condensation process of radiant panel and found the relationship between the condensation shape with temperature and relative humidity. Tang et al. [14] used simplified Navier–Stokes equations with Boussinesq approximation to study the condensation rates, and they found that the condensation rate on the radiant ceiling

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was 3.5 times greater than that on the radiant floor and 25% greater than that on the radiant wall. Ge et al. [15] used neural network based prediction method to predict condensation risk and the optimal pre-dehumidification time in radiant ceiling systems.

We can conclude that most studies are focused on using relative higher cooling water temperature, and parallel DOAS system to prevent condensation. Besides these methods, we found that the structure of CRCP also has influence on condensation. Fig. 1 shows the structure of one general CRCP and its surface temperature distribution [16]. Through the in-situ infrared image in the areas underneath the pipes, we found that dark blue bars are of lower temperature of 14–16 °C, and the rest blue areas are of higher temperature of 18–20 °C. This is because the pipes that chilled water flows past have close contact with the metal panels, which cause the surface temperature underneath the pipes is about 4 °C lower than the rest areas. In theory, to prevent panel surface condensation, minimum surface temperature is required to be higher than room dew point temperature. Moreover, it is good practice to maintain the supply water at or above the dew-point temperature, which limits the cooling capacity.

Instead, Fig. 2 shows a novel CRCP with uniform surface temperature distribution. This CRCP has good application in energy efficiency compared to over-head air-conditioning systems, and has better performance for condensation control in the south of China with hot humid weather conditions [17,18]. The reason lies in that if the surface temperature distribution is uniform, the moisture will not centralize on one point or one line, thus it is hard to accumulate into droplets. On the other hand, less moisture is needed for the CRCP with bar-shape temperature distribution, as the vapors tend to concentrate on the areas with lower temperature. However, the cooling capacity is decreased by about 38% compared to the general CRCP type with cooling capacity of about 95 W/m$^2$ [12]. We found it necessary to use temperature distribution as well as cooling capacity to have a comprehensive evaluation of the CRCP, due to the conflict between condensation prevention and higher cooling capacity demand. To analyze the cooling capacity and temperature distribution for this CRCP, we will use computer fluent dynamics (CFD) method for heat transfer simulation, and use experimental data to verify the reliability of the CFD simulation. In addition, we will propose improved panel types with higher cooling capacity and retained uniform temperature distribution.

## 2. The methodology of improving cooling capacity

Cooling capacity is one of the most important indexes to evaluate the thermal performance of CRCP. While the cooling capacity is expected the higher the better in engineering practice, it is limited due to the requirement of condensation control. In theory, the area with minimum surface temperature is the most vulnerable part where condensation first occurs on the panel. Thus, minimum panel surface temperature $T_{min}$ should be higher than room dew-point temperature $T_{dew}$, which limits the cooling capacity.

In general, the heat transfer between panel and room thermal environment includes heat exchange between room air temperature; and heat exchange between panel surface and mean radiant temperature. As indicated in a radiant system guidebook [5] and ISO 11855 2012 [9] standard: for low air velocities (<0.2 m/s), or where the difference between mean radiant temperature and air temperature is small (<4 °C), the operative temperature can be approximated with the simple average of air and mean radiant temperature. As most CRCP types meet these conditions, this operative temperature can be used as the reference temperature when calculating the heat exchange between the panel and room thermal environment. Therefore, the cooling capacity of panel can be expressed with an equation in relation to the indoor operative temperature $T_{op}$, panel average surface temperature $T_s$ and total heat transfer coefficient between the panel surface and room thermal environment $h_t$, as shown in Eq. (1).

$$q = h_t(T_{op} - T_s) \tag{1}$$

Where, $T_s$ can be approximately expressed as follows

$$T_s \approx T_{\min} + 0.5(T_{\max} - T_{\min}) = T_{\min} + 0.5\Delta T \tag{2}$$

By substituting Eq. (2) into Eq. (1), the cooling capacity for a CRCP can be expressed as

$$q = h_t(T_{op} - T_{\min}) - 0.5h_t\Delta T \quad (T_{\min} \geq T_{dew}) \tag{3}$$

Where, $\Delta T$ is the difference between maximum and minimum surface temperature, which indicates the temperature distribution of the panel. The value of $h_t$ and $T_{op}$ are the same for the specific room operative temperature and humidity ratio, therefore the cooling capacity can be regarded only relevant to $T_{min}$ and $\Delta T$. Furthermore, to prevent panel surface condensation, $T_{min}$ should be no less than $T_{dew}$. Therefore, from Eq. (3), it can be seen that, the smaller $\Delta T$, the larger the cooling capacity will be; which means the more uniform surface temperature distribution, the more exploitable cooling capacity will be. For instance, when $h_t = 10.8$ W/(m$^2$ K) according to ISO 11855-2 [10], the cooling capacity of the panel with $\Delta T = 0.5$ °C is 18.9 W/m$^2$ larger than the one with $\Delta T = 4$ °C. Therefore, to improve the cooling capacity, one possible solution is improving the panel structure to get more uniform temperature distribution. In addition, it's more comprehensive to use

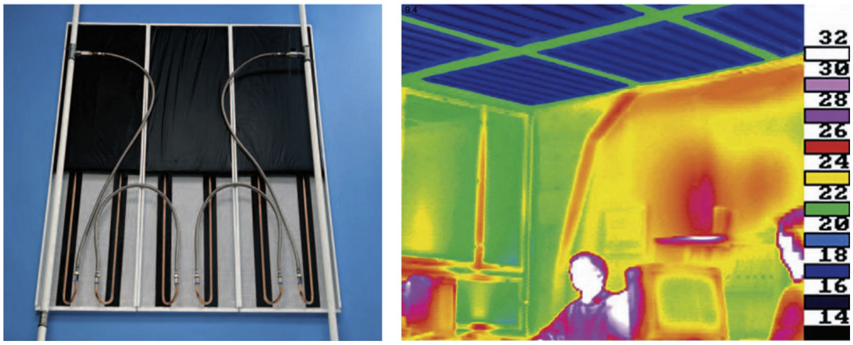

**Fig. 1.** A CRCP and its in-situ infrared image.