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Experimental Study on Cooling Characteristics of Concrete Ceiling Radiant Cooling Panel

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Abstract

Concrete ceiling panel cooling system had advantages of comfort and energy saving. This paper presented the experimental study on cooling characteristics of concrete ceiling radiant cooling panel. Temperatures of the concrete panel and indoor environment were measured and analyzed. The results showed that vertical temperature distribution of the indoor air was uniform and temperatures of inner surfaces of walls were close. Indoor sensible cooling load had significant effect on the final thermal environment of the room. The cooling rate of concrete panel was pretty slow and the response time was relatively long during condition adjustment. Thermal inertia of the concrete slab made control and adjustment of the system relatively difficult, however it also decreased the impact to indoor thermal environment from small fluctuation of supply water temperature.

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Keywords: Experimental study; Concrete ceiling radiant cooling panel; Steady state; Unsteady state

1. Introduction

In buildings with ceiling panel cooling system, heat was removed from the room by a combination of radiation and convection. Energy saving of ceiling panel cooling system had been proved relative to conventional all-air system. Heat was removed directly from human body by radiant heat transfer, and people felt more comfortable in rooms with ceiling panel cooling system [1-3]. Concrete ceiling panel cooling system was a type of ceiling panel cooling systems. Water tubes were embedded in the concrete during the construction phase. When the cold water was sent into the embedded tubes, the concrete slab was cooled gradually [4-6].

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Theoretical and experimental studies on ceiling panel cooling system were developed by researchers in recent years. Oxizidis and Papadopoulos found that appropriate control and evaluation of thermal comfort were pretty significant in order to take full advantage of radiant system [7]. Tye-Gingras and Gosselin developed a semi-analytical model for heat transfer calculation of radiant cooling or heating panels with serpentine tube layout [8]. Yin et al. studied the heat transfer performance and moisture condensation phenomenon of radiant cooling panels [9]. Tian et al. built the heat transfer model of the concrete slab by reaction coefficient method. Experiments were carried out to investigate steady and unsteady thermal performance [10].

The structure of concrete ceiling radiant cooling panel was similar to that of the radiant heating/cooling floor. Olesen and Michel investigated the heat exchange coefficient of floor cooling [11,12]. Li et al. proposed an analytical solution for heat transfer in a multi-layer floor structure of a radiant floor system. Experiments were conducted and results calculated by the analytical method were validated [13,14]. Jin et al. studied the effects of the thermal resistance of pipe and water velocity on the performance of the radiant floor [15].

According to the literature review, we thought we could do further experimental research on concrete ceiling panel cooling system.

Nomenclature

ε	emissivity of surface
h	heat transfer coefficient (W/m^2•K)
n	number of indoor surfaces
q	heat flux (W/m^2)
σ	Stefan-Boltzmann constant, 5.67×10^{-8}W/(m^2•K^4)
T	thermodynamic temperature (K)
t	temperature (°C)
Subscripts	
a	air
c	convective
p	panel
r	radiant

2. Theoretical analysis

Heat transfer of concrete ceiling panel cooling system consisted of several parts. Surfaces and air in the space transferred heat to the ceiling panel surface through radiation and convection. And panel surface transferred heat to external surface of the embedded tube through heat conduction. Then the external surface of the tube transferred heat to the internal surface. Heat was removed from internal surface of the tube by the chilled water through convection, and then the water flowed back to water chilling unit [16].

The net radiative heat exchange of the concrete ceiling radiant cooling panel (C-CRCP) equaled to subtract inward radiative heat exchange from the outward radiative heat exchange. The equation was:

$$q_r = \varepsilon_p \sigma T_p^4 - \sum_{i=1}^{n-1} X_{i,p} \varepsilon_i \sigma T_i^4 \quad (1)$$

The convective heat exchange of the C-CRCP was convective heat transfer coefficient multiplying temperature difference between panel surface and the air.

$$q_c = h_c \left(t_p - t_a\right) \quad (2)$$

3. Experimental setup

The C-CRCP chamber was located in Changsha, China [16]. It was built indoors to keep more stable environment and avoid the impact from sun and rain. There were two separate spaces in the chamber. The upper space was built to simulate upstairs of buildings. The C-CRCP was set between the two spaces and water tubes (Φ20mm) were embedded in the concrete slab. There were two separate circuits of embedded tubes. When the two circuits were both sent chilled water in operation, the distance of embedded tubes was 150mm. If only one circuit was used, the distance was 300mm. There was a window (720mm×510mm) on the west wall of the chamber. Inlets and outlets of tubes were all towards east. The outside size of the chamber was about 2000mm×2000mm×2820mm, and the size of lower space was approximately 1560mm×1560mm×1510mm. Most of the measurements were completed in the C-CRCP and the lower space. Construction materials and detailed sizes of the chamber were shown in Fig. 1.

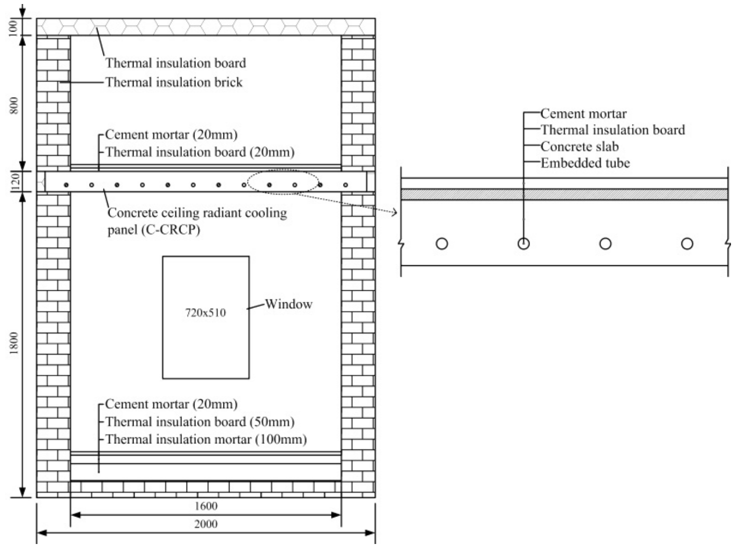


Fig. 1. Elevation of the C-CRCP chamber (Unit: mm).

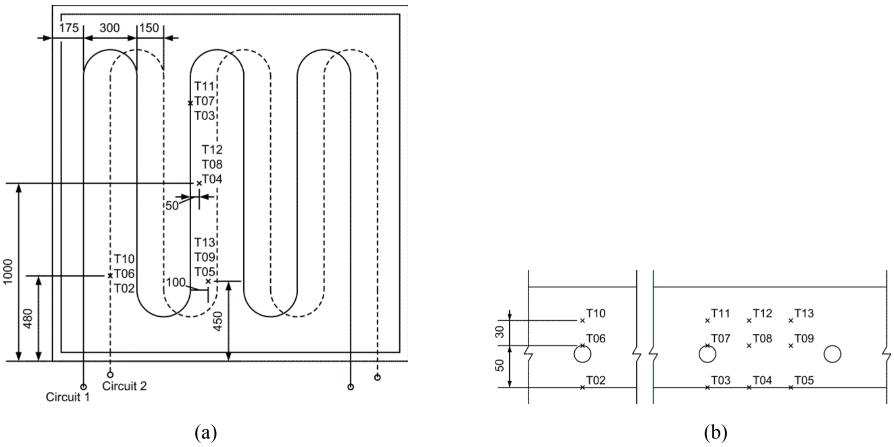


Fig. 2. Horizontal and vertical locations of sensors (Unit: mm).

There were twelve temperature measuring points (T02-T13) inside the concrete slab (Fig. 2). They were located on three horizontal surfaces and four measuring points each. Three temperature sensors were installed on each inner surface of the wall. There were also four temperature sensors on the panel surface and four on the floor surface. They were distributed evenly on the surfaces. There were three temperature sensors on the vertical line passing through the center of the chamber, and distances of the sensors to the floor were 375mm, 750mm and 1125mm respectively. Three temperature sensors were installed in the inlets and outlets to measure water temperatures (one for supply water and the other two for return water). All temperature sensors were PT-100 (accuracy: degree A, 0.15°C). Water flow rate was measured by water meter (accuracy: 0.0001 m^3/h).

4. Results and discussion

4.1. Steady state experimental results and analysis

Temperature distribution of surfaces and air in the room in the steady state embodied the thermal environment characteristics of ceiling panel cooling system. According to the steady state data, thermal comfort of ceiling radiant cooling environment could be further studied in the future.

Table 1. Experimental data of steady state

Measuring parameter	Experimental condition						
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Distance of tubes (mm)	150	150	300	300	150	150	300
Water flow rate (m^3/h)	0.3266	0.3349	0.2653	0.2640	0.3450	0.3400	0.1735
Heating power (W)	500	500	520	500	300	320	340

Table 1 showed basic parameters of seven experimental conditions. Due to the limitation of the experimental chamber, the area of the C-CRCP was small. The temperature differences between supply and return water of seven conditions were 0.7°C-1.4°C, while average temperature difference was 1.0°C.

Fig. 3 showed that air temperatures of upper, middle and lower part were very close in each condition. This result agreed well with literatures. There were two reasons for this phenomenon. Firstly, internal surfaces of wall and floor were cooled directly by the cooling ceiling through radiant heat transfer. The air nearby these surfaces was cooled by surfaces through convection. Heat exchange of radiation depended on temperature and emissivity of surfaces and angle factors among surfaces, and it had nothing to do with the distances among surfaces. Secondly, the air nearby the cooling ceiling panel was cooled directly through convective heat transfer, and the cool air was heavier and dropped down. Natural convection of air also made the vertical temperature distribution more even.

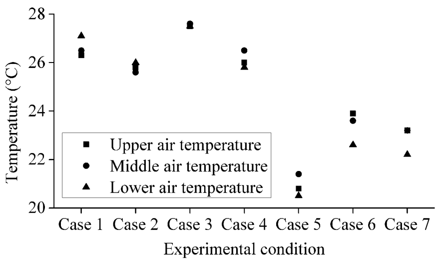


Fig. 3. Air temperatures of seven conditions

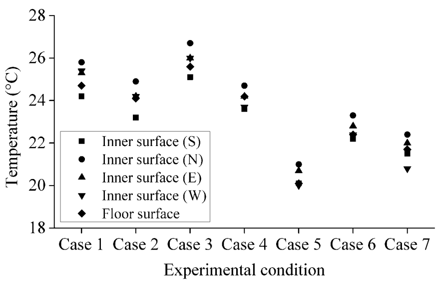


Fig. 4. Average temperatures of internal surfaces of walls of seven conditions

Temperatures of inner surfaces of walls were very close in each condition (Fig. 4). Because radiative heat transfer between cooling ceiling and other surfaces had no horizontal directivity. Temperature of inner surface of north wall was a little higher than others, that was because the heater was installed a little closer to the north wall owing to the space limitation.

Due to even distribution of air and surfaces temperatures, better thermal comfort of buildings with ceiling panel cooling system would be realized more easily.

Temperature in the C-CRCP (T03-T05, T07-T09) of seven conditions followed similar regularity of distribution when the distances of tubes were the same (Fig. 5). That was because heat transfer in the concrete abided by the same heat transfer law.

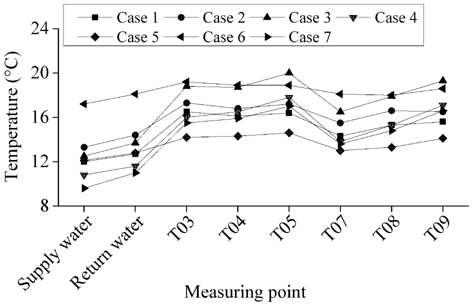


Fig. 5. Temperature in the C-CRCP of seven conditions

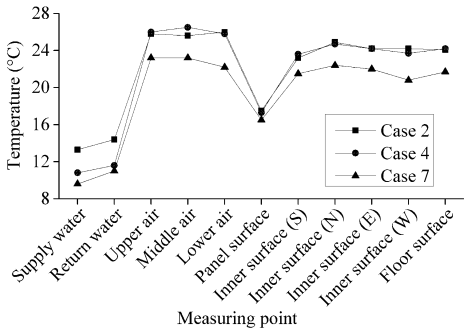


Fig. 6. Comparison of Case 2, Case 4 and Case 7

From the comparison of Case 2 and Case 4 in Fig. 6, it was found that when the average temperatures of ceiling panel surface were close in different conditions, temperature distributions of air and surfaces in the room were close, even though the supply or return water temperatures of the two conditions were obviously different. On the other side, the distance of tubes in Case 2 was 150mm, and the Case 4's was 300mm. This figure also showed that: in order to realize similar cooling effect, supply water temperature should be set lower if the distance of tubes was wider in practice.

From the comparison of Case 4 and Case 7 in Fig. 6, temperatures of supply water and return water were close, and distances of tubes of the two cases were the same too, but temperatures of air and surfaces were obviously different. The main difference between Case 4 and Case 7 was different water flow rate and heating power. Water flow rate of Case 4 was bigger than that of Case 7, while heating power of Case 4 was bigger than that of Case 7. Temperatures of air and surfaces of Case 4 were higher than those of Case 7. We could find from the comparison that heating power in buildings had big effects on the final indoor thermal environment.

The same conclusion could be made in Fig. 7. Supply water temperature of Case 6 was considerably higher than that of Case 1 or Case 2. The distances of Case 1, Case 2 and Case 6 were all 150mm and total water flow rate of the three cases were also quit close. But the final thermal environment of the three appeared very different. Temperatures of air and surfaces (non-cooling surfaces) of Case 6, which had the highest supply water temperature, were lower than corresponding temperatures of Case 1 or Case 2. The biggest difference among Case 6, Case 1 and Case 2 was the heating power. Case 6 was 320 W, Case 1 and Case 2 were both 500 W.

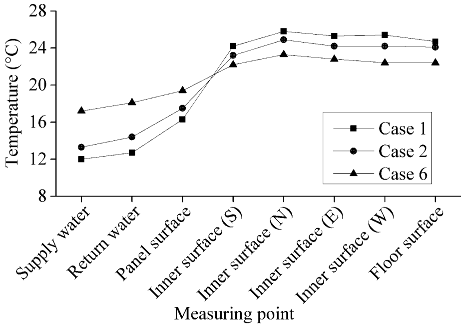


Fig. 7. Comparison of Case 6 and Case 1, 2

In practical operation, when indoor sensible cooling load changed, the surface temperature of ceiling radiant cooling panel need to be adjusted by changing the supply water temperature or flow rate. But if the cooling load rose too much, the final indoor temperatures may not meet the design requirement. So the indoor sensible cooling load in buildings should be fully considered during the requirements and design phases of the project.

4.2. Unsteady state experimental results and analysis

Unsteady heat transfer occurred during the start and stop phases or condition adjustment. It was very important to know the unsteady state characteristic of heat transfer for system control and adjustment.

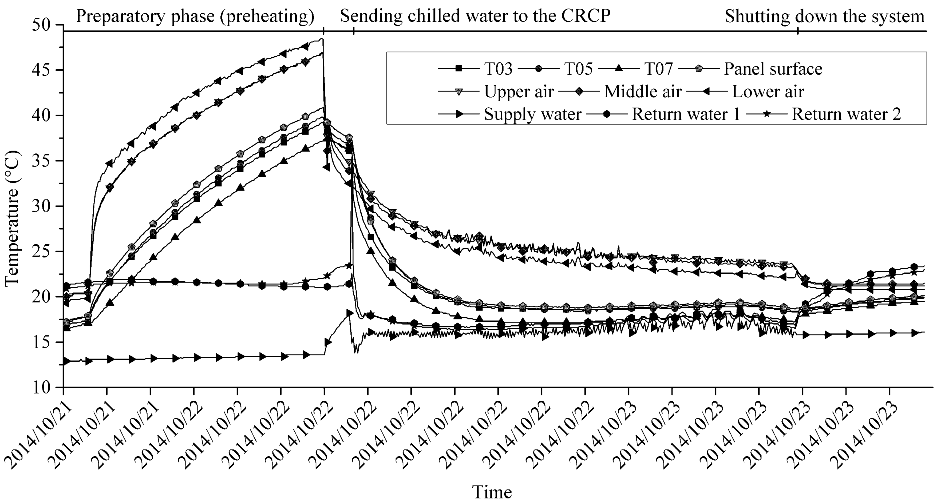


Fig. 8. Operation curves of concrete ceiling panel cooling system (Case 6)

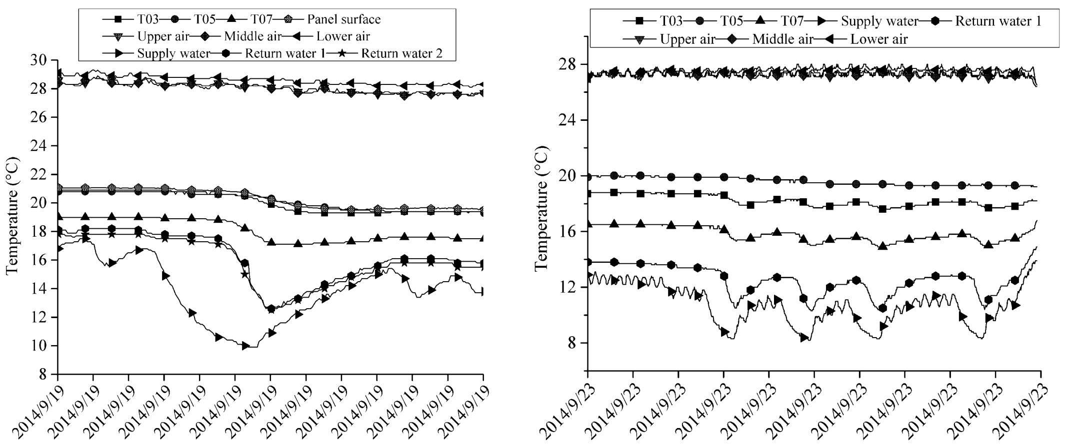
Fig. 8 showed the actual monitoring data of concrete ceiling panel cooling system in normal operation. The experimental date was Oct 21 to 23 in 2014. The ambient air temperature was 21°C-24°C during the experiment. In order to simulate high temperature condition in summer, the heater in the chamber was opened (heating power was 1000W) first before the chilled water was sent to the cooling panel. After heated about 14 hours, the heating power was turned down to 300W at 8:00 of Oct 22. After a while, air temperature in the chamber was approximately to 36°C, and temperatures of internal surfaces of chamber walls (non-cooling surfaces) were 31°C-35°C.

Chilled water of about 15°C was sent to the C-CRCP at 9:30 of Oct 22. The temperature of T07 dropped first, and then the temperature of ceiling panel surface dropped. The temperature of panel surface was about 37°C at 9:30, and then the temperature dropped down to 26°C at 11:20. The process of temperature dropping down was very slow due to the thermal inertia of the concrete slab.

Air temperatures inside the chamber were dropping slowly. Average air temperature inside the chamber was approximately 36°C at 9:30 and 26°C at 15:30. During the process of air temperature dropping down until stable, tendencies of the three measuring points of air appeared similarly. The fluctuating ranges of air temperatures were pretty small after reaching stable.

In Fig. 9(a), when supply water temperature dropped down, temperatures of return water, external surface of embedded tube (T07) and ceiling panel surface dropped down in turn and the ranges of drop also decreased in turn.

During 7:00-17:00 of Sep 23, the temperature of supply water fluctuated up and down just similarly to periodic fluctuation. The temperatures of return water, T07 and T03 also fluctuated periodically (in Fig. 9(b)). Periods of the four temperature fluctuations were quite close. Moments of troughs of the four temperature fluctuations were listed in Table 2. From the figure and the table, it was found that the trough of the latter delayed from the former gradually and amplitude of fluctuation of the four temperatures decreased gradually.



(a) (b)

Fig. 9. Temperature fluctuations in concrete ceiling panel cooling system.

Table 2. Moments of troughs of temperature fluctuations

Measuring point	Moments of troughs (hh:mm)			
	Trough 1	Trough 2	Trough 3	Trough 4
Supply water temperature (°C)	10:13	11:54	13:26	15:42
Return water temperature (°C)	10:16	11:57	13:29	15:45
T07 (°C)	10:17	12:02	13:33	15:48
T03 (°C)	10:39	12:11	13:40	15:53

Due to the impact from thermal inertia of the concrete slab, temperature fluctuation of panel surface delayed very much relative to supply water temperature and the temperature amplitude of panel surface was much smaller than that of supply water. Thermal inertia of the concrete slab made the control and adjustment difficult in ceiling panel cooling system, however it also decreased the impact to indoor thermal environment from small fluctuation of supply water temperature.

5. Conclusion

- In ceiling panel cooling system, vertical temperature distribution of the indoor air was uniform and temperatures of inner surfaces of walls were close too. This kind of thermal environment was benefit for thermal comfort of human body.
- For the same cooling effect, supply water temperature should be set lower if the distance of embedded tubes was bigger. Indoor sensible cooling load had significant effect on the final thermal environment of the room, so it should be fully considered during the requirement and design phases of the project.
- The adjustment method of ceiling panel cooling system was only the adjustment of supply water temperature or flow rate. The cooling rate of C-CRCP was pretty slow and the response time was relatively long during condition adjustment. Thermal inertia of the concrete slab made the control and adjustment difficult in ceiling panel cooling system, however it also decreased the impact to indoor thermal environment from small fluctuation of supply water temperature.

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