Condensation Control of Multi-zone DOAS + Ceiling Radiant Cooling Panel in Hot and Humid Region

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Abstract

DOAS(dedicated outdoor air system) combined with CRCP (ceiling radiant cooling panel)has been getting more applications around the world due to its advantages on thermal comfort and human health. However, condensation control of ceiling radiant cooling panel is usually a big concern when this system is applied, especially in hot and humid regions. This paper focuses on the study of the control strategies of multi-zone DOAS + ceiling radiant cooling panel system, intending to promote the further development and application of this hybrid system. Firstly the allowed minimum inlet water temperature of radiant cooling panels is investigated and a formulation is given to determine its value. Then, the paper proposes a practical control method for multi-zone DOAS +CRCP system applied in hot and humid regions, based on the study on allowed minimum inlet water temperature of CRCP. The control method is applied in a small project with DOAS+CRCP system installed in an office space with 172.4 sq.m. floor area and four thermal zones and test are conducted on two typical weather data. The test results show that indoor air temperature and humidity can be very well controlled while condensation is successfully avoided.

Keywords – condensation control; DOAS; CRCP; hot and humid region

1. Introduction

DOAS (Dedicated Outdoor Air System) has been developing increasingly and getting more applications in decades around the world.

DOAS has to be combined with such sensible cooling terminals as fan coil, radiant cooling panel and so on to meet the cooling demand. Among which, CRCP (ceiling radiant cooling panel) is preferred due to its advantages of thermal comfort and energy efficiency. However, condensation control of CRCP is usually a big concern when this system is applied, especially in hot and humid regions.

Mumma and his team did a lot of research on DOAS and viable parallel terminal systems, covering design issues of DOAS combined with parallel terminal systems[1,2,3], DOAS combined with CRCP[4,5] and control issues of DOAS[6,7]. Many other researchers around the world have also been involved in the research about DOAS; more focuses on its energy efficiency feature. Stetiu[8] estimated the energy and peak power savings potential of radiant cooling systems in US commercial buildings, based on numerical modeling of a radiant cooling system and an all-air system at different locations in USA; he found that the savings potential is climate dependent and is larger in retrofitted buildings than in new construction. Liu et al[9] did energy consumption analysis on a dedicated outdoor air system with rotary desiccant wheel combined with a desiccant dehumidification system and vapor compression refrigeration system. The results indicate that, compared with a conventional DOAS, energy savings are possible for the suggested DOAS, when solar energy or natural gas is used for regeneration. Imanari et al[10] compared CRCP and conventional air-conditioning system in terms of thermal comfort, energy consumption and cost. Some studied CRCP combined with displacement ventilation system [11,12]. However, a few studies have been conducted on humidity control issues of DOAS+CRCP [13].

This paper proposes a practical control method for multi-zone DOAS+CRCP in hot and humid regions, based on the study on allowed minimum inlet water temperature. This control method is applied in a small project in Shanghai, China and the test results show that condensation is successfully avoided while indoor air temperature and humidity are well controlled.

2. Condensation Control of CRCP

Condensation control is the most important issue when CRCP is applied in buildings located in hot and humid region, since once condensation occurs during operation, it will have negative influence on indoor environment, and it will make designers hesitate to use it when designing a new air conditioning system. In order to prevent condensation on the surface of CRCP while keeping its cooling capacity, the inlet water temperature of CRCP need to be controlled to ensure the surface temperature higher than the dew point temperature of room air. Therefore, we study the allowed minimum inlet water temperature of radiant cooling panels, by both simulation and experiment. We only study metal radiant panel, since its condensation control is more difficult than capillary types.

2.1 Finite element modeling

We use THERM, a two-dimensional heat transfer modeling tool developed by Lawrence Berkeley National Laboratory (LBNL), to develop a simulation model for metal cooling radiant panel. THERM uses two-dimensional (2D) conduction and radiation heat-transfer analysis based on the finite-element method, which can model the complicated geometries of fenestration products and other building elements. This method requires that the cross section be divided into a mesh made up of non-overlapping elements, which is performed automatically by THERM using the Finite Quadtree method[14]. The model is developed according to the dimension and heat transfer characteristics of the radiant panel used in experiment. The radiant panel consists of aluminum ceiling panel and insulation material. Table 1 gives the heat conductivity of the materials including air layer. Figure 1 illustrates the dimension of a metal radiant panel model.

Table 1. Heat conductivity of construction materials of radiant panel

Material	Insulation	Air	Aluminum
（$W/m^2 \cdot K$）	0.061	0.0517	237

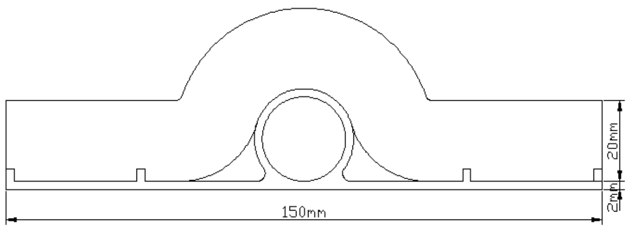

Fig. 1 Dimension of metal radiant panel model

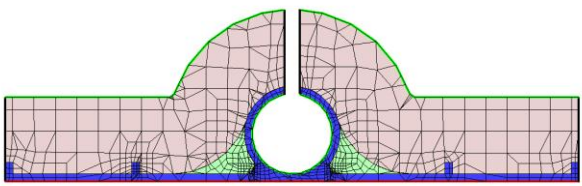

Fig. 2 Meshing of metal radiant panel model in THERM

In the analysis of heat transfer process, the convective heat transfer coefficient inside the tube is calculated with the equations recommended by Xia and Mumma [15]:
When Re<2300,

$$Nu = 3.657 \tag{1}$$

When Re$\geq$2300,

$$Nu = \frac{(f/8)(\text{Re}-1000)\cdot \text{Pr}}{1+12.7\sqrt{f/8}\cdot(\text{Pr}^{\frac{2}{3}}-1)} \tag{2}$$

$$f = \frac{1}{(1.82\cdot \log_{10}\text{Re}-1.64)^2}$$

Helmut[16] recommended the overall heat transfer coefficient (including natural convection coefficient and radiation heat transfer coefficient) on the lower surface of CRCP as 9~12 W/(m^2.K). Obviously larger is the overall heat transfer coefficient, larger the temperature difference between CRCP lower surface and air. As the room air temperature is higher than the surface temperature of CRCP in cooling conditions, if the overall heat transfer coefficient of the surface of CRCP is larger, the surface temperature of CRCP is higher and the possibility of condensation is less; vice versa. So in order to analyze the worst condition, the overall heat transfer coefficient of the surface of CRCP is assumed as 9 W/(m^2.K) in our study.

Figure 2 shows the meshing of metal radiant panel model in THERM and Tables 2 to 4 give the simulation results.

Table 2. Minimum surface temperature of CRCP with 26℃ room air temperature and 16 ℃ inlet water temperature

Model	Air temperature outside of insulation (^{o}C)	Convective heat transfer coefficient of the insulation surface (W/(m^2*K))	Water flow rate of CRCP (L/h)	Flow pattern	Minimum temperature of the surface of CRCP(^{o}C)
1	30	2	100	Laminar	18.2
2	30	2	250	Turbulent	16.4
3	30	2	300	Turbulent	16.3
4	33	2	100	Laminar	18.3
5	33	4	250	Turbulent	16.4
6	33	4	300	Turbulent	16.3

Table 3. Minimum surface temperature of CRCP with 26°C room temperature and 14 °C inlet water temperature

Model	Air temperature outside of insulation (℃)	Convective heat transfer coefficient of the insulation surface ($W/(m^2*K)$)	Water flow rate of CRCP (L/h)	Flow pattern	Minimum temperature of the surface of CRCP(℃)
1	30	2	100	Laminar	16.6
2	30	2	250	Turbulent	14.4
3	30	2	300	Turbulent	14.4
4	33	2	100	Laminar	16.7
5	33	4	250	Turbulent	14.5
6	33	4	300	Turbulent	14.4

Table 4. Minimum surface temperature of CRCP with 24℃ room temperature and 16℃ inlet water temperature

Model	Air temperature outside of insulation (°C)	Convective heat transfer coefficient of the insulation surface ($W/(m^2*K)$)	Water flowrate of CRCP (L/h)	Flow pattern	Minimum temperature of the surface of CRCP(°C)
1	30	2	100	Laminar	18.2
2	30	2	250	Turbulent	16.3
3	30	2	300	Turbulent	16.3
4	33	2	100	Laminar	18.3
5	33	4	250	Turbulent	16.3
6	33	4	300	Turbulent	16.3

From the simulation results, it can be found that:

a. The convective heat transfer coefficient of the insulation surface and room temperature almost has no effect on the difference between the inlet water temperature and the minimum surface temperature of CRCP;

b. The flow pattern inside the tube has impact on the difference between the inlet water temperature and the minimum surface temperature of CRCP, but under the same flow pattern, the effect of the water flow rate is very little;

c. With a certain CRCP construction, in the same water flow rate, the difference between the inlet water temperature and the minimum surface temperature of CRCP is a constant. In this article, the temperature difference can be considered as 0.4 °C.

According to relative researches [17,18], maintaining the surface temperature of CRCP 1°C higher than the room air dew point temperature can prevent condensation effectively on the surface of CRCP while keeping its cooling capacity. Considering the 0.4°C temperature difference between inlet water and CRCP surface obtained from simulation, the allowed minimum inlet water temperature of CRCP can be written as:

$$T_{wi}=T_{dew}+1-\triangle T \quad (3)$$

Where: T_{wi} – Allowed minimum inlet water temperature of CRCP, °C

T_{dew} – Dew point temperature of room air, ^{o}C

ΔT – Difference between inlet water temperature and surface temperature of CRCP, ^{o}C

In this study, we define: $T_{wi}=T_{dew}+0.5$ ℃.

2.2 Condensation experiment

Condensation experiments are conducted on a test bed, which is located in Tongji University, Shanghai, China. Five experiments with different inlet water temperatures are carried out and the results prove that the proposed method (i.e., maintaining inlet water temperature $0.5^{o}C$ higher than room air dew point temperature) is effective in preventing condensation on the panel surface while maintaining the maximum cooling capability of radiant cooling panel. Table 5 presents the results of five experiments.

Table 5. Experiment of allowed minimum inlet water temperature of CRCP

Experiment	△T (℃)	Experiment time (min)	Condensation time (min)
1	0.5	130	/
2	-1	80	80
3	-2	70	70
4	-2	100	/
5	-3	50	10

3. Control Strategy of Multi-zone DOAS+CRCP System

Based on the study on allowed minimum inlet water temperature, we propose a practical control method for multi-zone DOAS + ceiling radiant cooling panel system applied in hot and humid regions. Figure 3 illustrates the control strategy of this system. In this system, each individual thermal zone is equipped with sensors to detect indoor temperature and humidity and cooling is provided by a separate water circuit by adjusting the inlet water temperature of the ceiling in each zone. Meanwhile, the dew point of each zone is calculated and the inlet ceiling water temperature is controlled so as to avoid condensation on the panel. In such critical weather conditions when outdoor humidity is relatively high, the inlet water temperature increases so that the cooling capacity of ceiling panel decreases. The control system will automatically reduce the supply air temperature of DOAS, to compensate for the lack of ceiling cooling capacity and reduce indoor humidity as quickly as possible. Once the indoor air humidity falls back to a safe value, the inlet ceiling water temperature continues to be controlled by the indoor temperature settings and the cooling capacity of ceiling radiant panel reaches the maximum level.

4. Case Study

This control method is applied in a small project with DOAS + ceiling radiant cooling panel system installed in an office space with 172.4 sq.m. floor area and four thermal zones. The total design cooling load is calculated as 24.06 kW and moisture load is 13.13kg/h with design indoor condition as 25°C and 50% RH.

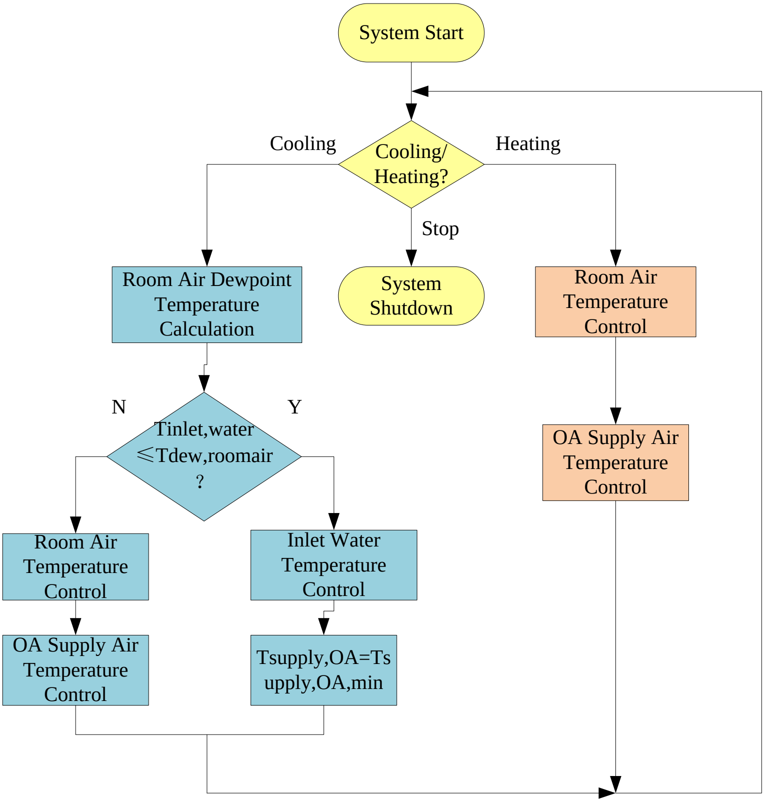

Fig. 3 Flow diagram of control strategy for multi-zone DOAS + CRCP system

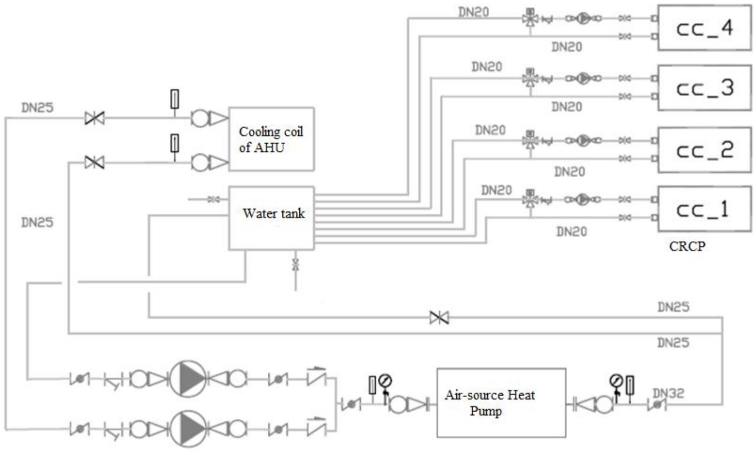

Fig. 4 Schemetic of case study DOAS+CRCP system

Figure 4 shows the system configuration of the project. In this project, each individual thermal zone is equipped one CRCP and the inlet water temperature of the each CRCP is adjusted by mixing the supply water from the water tank and the return water from CRCP with a three-way valve in the separate water circuit. An air-source heat pump produces chilled water in 6 to 7 ^{o}C for DOAS to ensure sufficient dehumidification of outdoor air, as well as the chilled water of CRCP.

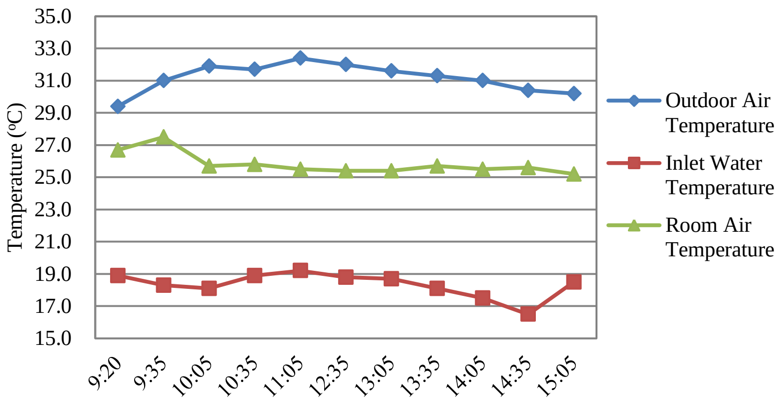

Fig. 5 Testing results of temperatures on July 3rd, 2009

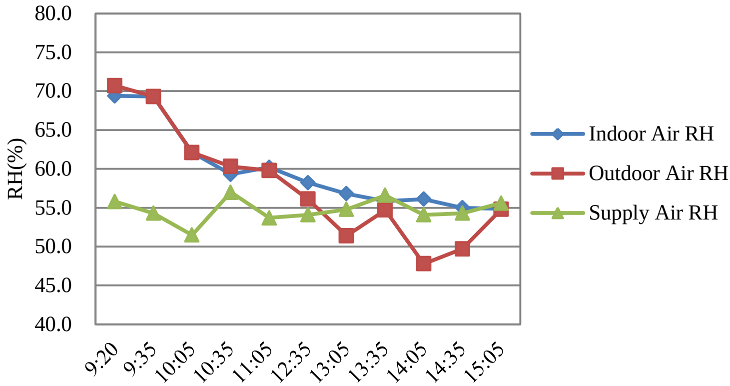

Fig. 6 Testing results of RH on July 3rd, 2009

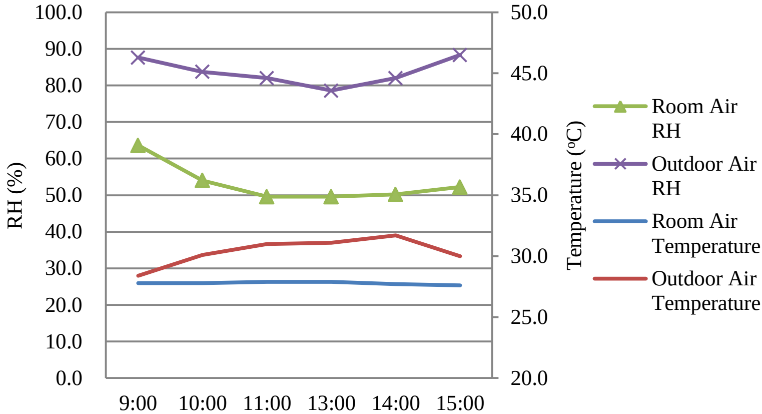

Fig. 7 Testing results of temperature and RH on July 10^{th}

The temperature and humidity of outdoor air, indoor air as well as inlet water temperature of ceiling radiant panel are monitored and recorded in two typical weather days – one hot and dry day and one hot and humid day. Figures 5 to 7 show the testing results.

The test results show that indoor air temperature and humidity can be very well controlled while condensation is successfully avoided on both two days.

5. Conclusion

In order to prevent condensation on the CRCP surface, we define allowed minimum inlet water temperature of radiant cooling panel and give a formulation to determine its value based on simulation: $T_{wi}=T_{dew}+1-\Delta T$. Five experiments with different panel inlet water temperatures are carried out and the results prove that this formulation and method is effective in preventing condensation on the panel surface while maintaining the maximum cooling capability of radiant cooling panel. Furthermore, a practical control method is proposed for multi-zone DOAS + ceiling radiant cooling panel system applied in hot and humid regions.The control method is also validated by a real project, in which, testing results show that indoor air temperature and humidity can be very well controlled while condensation is successfully avoided.

6. References

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