Experimental Study on Indoor Thermal Environment of Capillary Radiant Cooling Based on Different Installation Methods

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Abstract. The paper, taking the room of an office building as an example, makes a comparison on the changes of response, indoor temperature field and cooling surface temperature between the capillary radiation cooling ceilings and walls at 16℃ and 18℃ through the experimental study. The results show that: 1) when the water supply temperature is set to 16℃ and 18℃, the indoor temperature can meet the design requirements when the system works stably. 2) No matter what types of radiant cooling is used, the indoor temperature drop rate increases with the decrease of water supply temperature. In the height range of 0.7m to 1.5m from the ground, the temperature drop rate of radiant cooling ceilings is 1.8-2.4°C/h, and that of radiant cooling wall is 0.8-1.1°C/h. 3) When the system reaches the stable phase, the wall cooling system presents a state of "lower cooling and upper heating", and the radiant cooling ceilings presents a state of "upper and lower cooling, middle heating", but the horizontal and vertical maximum temperature difference does not exceed 2.0°C, which meets the thermal comfort requirements of the human body.

1. Introduction
As energy and environment have increasingly become the focus of public attention, China has issued a series of policies, regulations, reward and punishment mechanisms to achieve the goal of controlling the total amount of energy consumption and reducing carbon emissions [1]. Therefore, under the background of ensuring the comfort of indoor climate and reducing the energy consumption of heating and air conditioning, radiant air conditioner has become the focus of research because of its high comfort, many choices on low-grade heat energies and great energy saving potential[2]. In 2002, the United States Department of Energy listed radiant air conditioner as one of the fifteen key energy-saving technologies of the air conditioner that to be developed in present and the future [3].

The results show that under the same thermal sensing, the radiant cooling system can increase the indoor air design temperature by 1~2°C, and its cooling load is 10% ~ 20% lower than that of the normal air conditioning system so that to realize energy-saving of the system[4-5]. Radiant air conditioner has been used in Europe for 30 years. However, the outdoor air is humid in summer in most parts of China, which limits the normal use of radiation air conditioner. In recent years, many experts have put forward the form of air conditioning system which combines radiant air conditioning with dehumidification system, in which the fresh air bears the indoor wet load and the sensible heat bears the indoor sensible heat load, thus to create conditions for the application of radiant air conditioner in summer and become the most effective system form of radiant air conditioner[6-8]. This paper makes an experimental study on the indoor thermal and humid environment of radiant
cooling ceiling and wall, and makes a comparative analysis from the aspects of indoor thermal environment characteristics, indoor temperature response rate, enclosure structure corresponding speed and so on.

2. Experimental research program

2.1 Laboratory room
The radiant cooling lab room is located in an experimental building of Chongqing University. Room 2 and Room 3 are experimental rooms. The enclosure structure, orientation, area and window-wall ratio of the two rooms are consistent, and the building plan is shown in Figure 1. In which, the experimental Room 1 is the ceiling radiant cooling, and the experimental room 2 is the wall radiant cooling.

![Figure 1. Plane Graph of the Lab and Image of the Lab](image)

2.2 Test parameters and apparatus
The test parameters mainly include the wall temperature of the enclosure structure, the indoor and outdoor air temperature and the outdoor temperature and humidity.

| Apparatus Name | Model         | Measurement Range                  | Error        |
|----------------|---------------|------------------------------------|--------------|
| T-shape Thermocouple | /            | -40→+125°C                         | ±0.5°C       |
| Agilent data acquisition apparatus | Agilent 34970A | -200→+350°C                         | /            |
| Black-bulb thermometer | HOBO/UX100-011 | Temperature: -20~70°C, RH:1%~95% | Temperature:0.21°C, RH:±3.5% |
| Thermal imager | FLIR T650sc   | -40°C~150°C                         | 1% of the reading |

The test points of the capillary network of the room are distributed as a quincunx, with a total of 28 temperature measuring points. The indoor space measuring points are distributed in the three equal division lines of the floor diagonal line. At the same time, in order to measure the indoor air temperature, thermocouple probes are arranged at the heights of 0.1m, 0.6m, 0.9m, 1.1m, 1.4m, 1.7m, 2.2m and 2.5m respectively, with a total of 25 temperature measuring points.
2.3 Experimental conditions
The experiment was carried out from July to August 2016. For the forms of ceiling radiant cooling and wall radiant cooling, the relevant parameters of indoor thermal and humid environment were measured continuously. Because of high temperature and high humidity in summer in Chongqing, combined with the analysis of pre-experimental results, the capillary water supply temperature 16°C and 18°C were respectively set in this study to avoid radiation surface condensation and to provide sufficient refrigerating capacity.

3. Test Results and analysis

Under water supply temperature of 16°C and 18°C, the response changes of ceiling radiant cooling and wall radiant cooling, indoor temperature field and surface temperature of enclosure structure are analyzed as follows.

3.1 Comparative analysis of response changes

As shown in Figure 2 and Figure 3, according to the fluctuated changes in indoor temperature, it is found that the temperature responds quickly from 8:00 to 9:00, which is defined as the start-up phase, the indoor temperature fluctuates from 9:00 to 23:00, with little change, and is defined as the stable phase. From 23:00 to the 7:00 a.m. of the next day is downtime, the temperature attenuates rapidly, and is defined as the Decrease phase.

3.1.1 Start-up phase

According to the Code for the Design of Heating, Ventilation and Air Conditioning for Civil Buildings, the indoor design parameters of comfort air conditioning should be 13024-28°C [9]. In this paper, 27°C of the indoor dry bulb temperature is taken as the design temperature. According to the temperature curves of the two water supply methods, the temperature drop of the ceiling radiant cooling and wall radiant cooling are calculated, as shown in the table below.

| Operating Temperature | Type                | Operating Time |
|-----------------------|---------------------|----------------|
| 16°C                  | Ceiling capillary   | 8:00-23:00     |
| 18°C                  | Wall capillary      |                |
|                       | Ceiling capillary   |                |
|                       | Wall capillary      |                |

Table 2. Experimental Plan

![Figure 2. Indoor temperature changes of radiant ceiling under different water supply conditions](image1)

![Figure 3. Indoor temperature changes of radiant wall under different water supply conditions](image2)
Table 3. Comparison of temperature drop between ceiling cooling and wall cooling in start-up phase

|                              | Ceiling radiant cooling | Wall radiant cooling |
|------------------------------|-------------------------|----------------------|
| Operating Temperature(°C)    | 16                      | 18                   |
| Initial indoor temperature(°C) | 29.0                    | 28.8                |
| Temperature after an 1h      | 26.6                    | 27.2                |
| Temperature drop rate(°C/h)  | 2.44                    | 1.80                |
| Temperature drop to 27°C     | 8:35                    | 9:45                |
| Time needed for the          | 0.58h                   | 1.75h               |
| temperature drop to 27°C     |                         | 1.33h               |
|                              |                         | 12.6h               |

As can be seen from the table, in the start-up phase, the ceiling and walls show the following rules, that is, the lower the water supply temperature, the faster the initial temperature drop rate. At the same water supply temperature, the roof temperature drop rate is faster than that of the wall. At 16°C, it takes 35 minutes and 80 minutes to decrease to the indoor set temperature respectively, while at 18°C, it takes 105 minutes and 12.6 hours to drop to the same temperature.

3.1.2 Stable phase

Based on the above definition and test data, an comparative analysis is made between the minimum temperature and the existence time of the minimum temperature of ceiling radiant cooling and wall radiant cooling under two different water supply temperatures. The conclusion is shown in the following table.

Table 4 Temperature drop comparison between ceiling cooling and wall cooling in stable phase

|                              | Ceiling radiant cooling | Wall radiant cooling |
|------------------------------|-------------------------|----------------------|
| Operating temperature(°C)    | 16                      | 18                   |
| Minimum room temperature (°C) | 25.7                    | 26.3                |
| Time of the minimum room      | 20:25                   | 20:30               |
| temperature                   | 20:25                   | 20:55               |
| Temperature drop rate(°C/h)   | 0.07                    | 0.08                |
|                              |                         | 0.12                |
|                              |                         | 0.01                |

Therefore, in the stable phase, no matter which types of radiant cooling it is, with the decrease of water supply temperature, the minimum temperature of the room decreases in turn. At 16°C, both ceiling radiant cooling and wall radiant cooling can quickly meet the design requirements of 27°C within one hour, and the ceiling can quickly reach the lowest indoor temperature at 18°C. Although the wall radiant cooling under the working condition of 18°C can finally meet the design requirements, its system running time of is relatively longer.

3.1.3 Decreasing phase

Similar to the start-up phase and the stable phase, recording the temperature rise of different water supply temperature of different types of radiant cooling in decreasing phase, and the conclusion is shown in the following table.
Table 5. Temperature drop comparison between ceiling cooling and wall cooling in decreasing phase

|                                | Ceiling radiant cooling | Wall radiant cooling |
|--------------------------------|-------------------------|----------------------|
| Operating temperature (°C)    | 16 18                   | 16 18                |
| Temperature at 23:00 (°C)     | 25.7 26.3               | 25.3 26.9            |
| Room temperature after 5 hours shutdown (°C) | 20:25 20:30 | 20:55 21:35 |
| Temperature rise rate(°C/h)   | 0.07 0.08               | 0.12 0.01            |

As a result, it can be found that in the decreasing phase, the indoor temperature rise rate tends to increase with the decrease of water supply temperature. In the 5 hours after the shutdown, the indoor temperature drops rapidly, and then keeps rising, but the decreasing is slow, and generally follows the rules of first fast and then slow, and finally tends to be stable, and under the same temperature, the temperature rise rate of the wall is less than that of the ceiling.

3.2 Comparative analysis of indoor temperature field

3.2.1 Horizontal temperature distribution
The paper selects four important heights of 0.1m, 0.6m, 1.1m and 1.7m for data analysis. They are the height of human ankle, the height of the human knee, the top of the head the human sitting, and the top of the head the human standing. Based on the measuring points of different positions, the horizontal temperature differences are respectively calculated and the maximum horizontal temperature difference between ceiling radiant cooling and wall radiant cooling under different water supply conditions is obtained. The results are shown in the table below.

Table 6 Maximum temperature difference distribution at different heights in the horizontal direction

| Height | Ceiling radiant cooling (°C) | Wall radiant cooling (°C) |
|--------|------------------------------|---------------------------|
|        | 16 18                        | 16 18                     |
| 0.1m   | 0.5 0.8                      | 1.0 1.0                   |
| 0.6m   | 0.3 0.3                      | 0.8 1.0                   |
| 1.1m   | 0.2 0.1                      | 0.7 1.1                   |
| 1.7m   | 0.7 0.6                      | 0.8 0.9                   |

3.2.2 Vertical temperature distribution
The thermocouple temperature of radiant ceiling and radiant wall under the water supply temperature of 16°C and 18°C are recorded respectively, and the temperature distribution at nine measuring points is plotted, as shown in the following Fig.

From Figure 4 to 7, it can be seen that in the vertical direction of the temperature field, different cooling system are obviously different at the same water supply temperature, and the same cooling system are also different at different temperatures.
The temperature of each measuring point in the vertical direction of ceiling radiant cooling is different, the closer to the ground and the ceiling, the lower the temperature is, and the higher the temperature is when away from the ground and the ceiling, showing that "high at both ground and ceiling and low in the middle". This phenomenon is formed by the heat transfer principle of radiant cooling. The radiant panel is the cooling side, and the air is cooled by the radiant panels with lower temperature, so the wall temperature should be lower than the air temperature.

While the wall radiant cooling is different in the vertical direction, the closer the ground is, the lower the temperature is. The reason is that, on the one hand, the wall transfers the radiant heat to the adjacent ground, and on the other hand, the air with the decreasing temperature sinks rapidly because of the increase of density. It is worth mentioning that whether it is ceiling radiant cooling or wall radiant cooling, the maximum difference of temperature in vertical direction does not exceed 2°C. According to reference [6], if the temperature gradient at the head and ankle reaches about 2.0°C, the dissatisfaction is 2%.
3.3 Comparative analysis of cooling surfaces

![Figure 8. Ceiling surface temperature changes under different water supply conditions](image1)

![Figure 9. Wall surface temperature changes under different water supply conditions](image2)

Compared the surface temperature changes of ceiling and wall under 16°C and 18°C water supply conditions. The specific results are shown in Figure 8 and Figure 9.

4. Conclusions

Based on the experimental results, the following conclusions are obtained:

1) When the water supply temperature is set to 16°C and 18°C, the indoor temperature can meet the requirements of the indoor design parameters, either it is the ceiling radiant cooling system or the ceiling radiant cooling system.

2) No matter which types radiant cooling system, the temperature drop rate increases with the decrease of water supply temperature. In the working area of human body, the temperature drop rate of ceiling radiant cooling is 1.8-2.4°C/h. The temperature drop rate of wall radiant cooling is 0.8-1.1°C/h.

3) There are different indoor temperature field at different cooling system. The wall cooling system presents the state of "lower cooling and upper heating" while the ceiling radiant cooling presents "upper and lower cooling, middle heating", but the horizontal and vertical maximum temperature difference does not exceed 2.0°C, which meets the thermal comfort requirements of human body.

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