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Performance Evaluation and Experimental Study of the Induction Radiant Air-conditioning System

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Abstract

In this paper the air-conditioning system which combined the inducement ventilation and radiant air-conditioning is proposed. The indoor terminal device is the induction unit which is processed to be combined with the radiant panel on which the copper pipes with rigid aluminum diffusion fins are installed. The radiant panel can be cooled and heated by both water and air. The two-stage evaporator chiller with the non-azeotropic refrigerant is utilized in the system. The experiments of performance test for the novel air type induction radiant air-conditioning system were carried out to verify the feasibility of the system. With the radiation to heat the building envelope of the laboratory, the system can form an overall uniform indoor temperature field both in the vertical direction and the horizontal direction. When the upside return air inlet which shown better performance was used, the space under height 2m had a moderate temperature difference. The system can greatly reduce the sensation of draught which reduces comfort.

Keywords: Radiation; Experimental validation; Inducement ventilation; Air-conditioning system

1. Introduction

In recent years, the issue of comfort air conditioning system attracted widespread attention. Because of the outstanding comfort and high system efficiency, the radiant air-conditioning system attracted the attention of the researchers and manufacturers and had many practical applications [1,2]. In Europe which has the relatively dry climatic conditions, the water type ceiling radiant air-conditioning system and the radiant floor heating system are widely used in various constructions. But in Asian countries, only a few office buildings and hospitals began to use...
the systems. The application of this technology met some obstacles in the United States [3,4,5,6,7]. The main reasons are: In the regions where the climate is humid, the condensation often happens. The system has high cost due to the aforementioned and other problems. At present, the domestic and foreign researches focused on water type radiant air-conditioning. Many experts and scholars proposed to combine the radiation air-conditioning and dehumidification system to form an air-conditioning system which can independently control the temperature and humidity [8,9,10], which created the possibility of the application in wet areas. Although the technology overcame the problem of condensation to a certain extent, the system was becoming more difficulty to maintain and more complex. The increased equipment and space brought more cost.

To solve the issues, the induction radiant air-conditioning was proposed in this paper. In the air type system, with the air pressure, the indoor air is induced and mixed with the primary air. The mixed air is rectified and blown into the interior after heating/cooling the radiant panels. By increasing the temperature difference between the primary air and the indoor temperature, the air supply volume is reduced, which decreases the energy consumption and the noise for supplying the air. The two-stage evaporator with the non-azeotropic refrigerant is utilized in the system to reduce the equipment cost and space. To verify the feasibility and test the coupling effect of air type induction radiant air-conditioning and compare the performance and comfort with the traditional air conditioning, the experiments were carried out.

### Nomenclature

| Symbol | Description |
|--------|-------------|
| M      | the metabolism, W/m² |
| W      | the workload, W/m² |
| C      | the convective heat loss, W/m² |
| R      | the radioactive heat loss, W/m² |
| Esw    | the evaporative heat loss from skin surface, W/m² |
| Edif   | the perspiration, W/m² |
| Cres   | the respiratory sensible heat loss, W/m² |
| Eres   | the respiratory latent heat loss, W/m² |
| η      | the energy utilization factor |
| tp     | the return air temperature, °C |
| tn     | the average temperature of the indoor air, °C |
| t₀      | the supply air temperature, °C |

### 2. The Experimental System

#### 2.1. The introduction of the laboratory

Figure 1 shows the experimental system. The indoor terminal device is the induction unit which is processed to be combined with the radiant panel on which the copper pipes with rigid aluminum diffusion fins are installed. The radiant panel can be cooled and heated by both water and air. In air type which is different with the traditional radiant air-conditioning system, with the air pressure, the indoor air is induced and mixed with the primary air. The mixed air is rectified and blown into the interior after heating/cooling the radiant panel. The two-stage evaporator chiller with the non-azeotropic refrigerant is utilized to meet the induction radiant unit and the air handling unit. The water from the chiller is supplied to the air handling unit to cool/heat the primary air. Then the air is supplied to the induction radiant panel. In air type, the two evaporators operate in series mode to produce primary air with low temperature. The opened valves are V1, V2, V3, V4, V6, V7, and V9. In water type, the two evaporators operate in parallel mode to supply water to both the induction radiant unit and the air handling unit. The opened valves are V1, V2, V3, V4, V5, V8, V9, V10 and V11. The size of the laboratory is 7.5 m (d) × 3.75 m (w) × 2.6 m (h). The windows are installed on the north wall. The experiments utilized three air type induction radiant panels (The structure is shown in Fig 2) and four LED linear lightings. The temperature of the primary air is controlled by the
current signal output from the radiation temperature sensor which is installed in the central ceiling. In order to
calculate with the traditional air conditioning, on the north side of the laboratory a suspended indoor air conditioner
is installed nearby the window. Table 1 shows the parameters of the induction radiation panel.

Fig. 1. the experimental system

Fig. 2. cross section of the Induction radiation panel

| Table 1. Parameters of the Induction radiation panel |
|----------------------------------------------|
| **SLM – 200S** |
| Standard air volume                          | 200/m³·h⁻¹ (180~240/m³·h⁻¹) |
| Inducted mix air volume                      | 330/m³·h⁻¹                   |
| Supply air temperature                       | Cooling:13~16/°C Heating:40~42/°C |
| Inducted mix air temperature                 | Cooling:+6~+15/°C Heating:+4~+6/°C |
2.2. The experimental program

The prototype of the induction radiation panel is the modified indoor unit of VAV air conditioner. The indoor unit was added the aluminum radiation plate and its structure was manufactured with the corresponding processing. The three induction radiation panels can be controlled respectively to run and stop. When the three induction radiation panels run simultaneously and keep the indoor temperature stable, the air volume and heating power were changed by manually closing 1-2 induction radiation panels. The influence to the energy consumption and indoor thermal environment can be studied.

Heating temperature setting: Induction radiation panel and the traditional air conditioning were both set to 20°C, 22°C and 24°C. In addition, in order to study the influence of the location of the return air duct to the performance of the induction radiation panel, the experiments were carried out with the upside and downside return air ducts.

2.3. The measurement points

Four straight bars were set in the laboratory. 12 measurement points were set on every bar and. 18 measurement points were set at 1.1 m above the floor to collect the horizontal temperature distribution of the laboratory. Wall temperatures were collected at three heights of 0.5 m, 1.3 m and 2.1 m.

3. Evaluation Criteria

The most important advantage of the radiant air conditioning is the high comfort air-conditioned environment, which include the uniform and stable temperature distribution in the horizontal direction and vertical direction. In order to experimental verify the advantages of the air type induction radiant air conditioning compared to the traditional air conditioning, the following parameters related to the comfort and the indoor temperature distribution measured by the temperature sensors were collected and compared.

3.1. PMV (predicted mean vote)

PMV was proposed by Fanger [11] in 1970 as International Standard ISO-7730.

In order to predict the thermal neutral feeling, the linear relationships between the activity level and sweat rate, skin temperature were substituted into the heat balance equation to form the comfort equation. This equation expressed the relationship of the six environmental factors when the body is in the state of hot neutral and the numerical expression of the majority of people’s feeling in certain conditions.

\[
PMV = \left(0.303e^{-0.036W} + 0.028\right) \times \left(M - \dot{W} - C - R - E_{sw} - E_{dif} - C_{res} - E_{res}\right) \quad (1)
\]

3.2. ET* (new effective temperature)

In 1971 Gagge proposed the apparent temperature theory, and a new indoor thermal environment evaluation parameter ET*: When the relative humidity was 50% the average human body temperature, skin moisture and the six environmental factors were collected to calculate the comprehensive evaluation parameter in steady-state thermal environment.

ET * is defined in arbitrary metabolic rate and the amount of dressing. So with different metabolic rates and amounts of dressing ET* cannot be used to compare. Therefore, standard effective temperature (SET*)[12] was defined in the condition when the dressing amount was 0.6 clo, where clo is the unit of dressing amount, light office work was 1.0-1.2 met, where met is the unit of metabolism, airflow was 0.1-0.15 m/s, relative humidity was 40%-60% and mean radiant temperature MRT=atmospheric temperature.
4. Results And Discussion

4.1. Comparison with different return air inlets

In order to study which airflow organization form has the best coupling effect with the radiation air-conditioning, the influence of the different return air inlets was researched. First the radiation panels were not used and there were no heat source in the lab. Only the airflow organization form itself was studied. The airflow organization form can be changed by switching the air valves. For the induction radiant air-conditioning system, the uniformity of the airflow distribution affects the uniformity of the energy distribution. So the energy utilization factor can evaluate the airflow distribution. It can be expressed by:

\[
\eta = \frac{t_p - t_o}{t_n - t_o}
\]  

Table 2. The energy utilization factor with different return air inlets

| Air changes per hour | 1.3 | 2.7 | 4.0 | 5.3 | 6.7 | 8.0 |
|----------------------|-----|-----|-----|-----|-----|-----|
| Upside               | 1.50| 1.12| 1.03| 0.94| 0.90| 0.89|
| Downside             | 0.69| 0.88| 0.91| 0.92| 0.94| 0.95|

From the result in Table.2 it can be found that when the upside return air inlet was utilized, the energy utilization factor decreased with the increasing of the air change rate and was greater than 1.0 when the air change rate was smaller than 4.0. When the downside return air inlet was utilized, the energy utilization factor was close to 1.0 when the air change rate was greater than 4.0. The heat transfer efficiency of the upside return air inlet was better than downside return air inlet. When four virtual heat sources the power of which was 240W were installed in the lab, the energy utilization factor with different return air inlets were collected and compared.

Table 3. The energy utilization factor with different return air inlets (Virtual heat sources installed)

| Air changes per hour | 2.7 | 4.0 | 5.3 | 6.7 |
|----------------------|-----|-----|-----|-----|
| Upside               | 1.09| 1.10| 1.12| 1.14|
| Downside             | 0.81| 0.90| 0.92| 0.94|

From the result in Table.3 it can be found that with the virtual heat sources the heat transfer efficiency of the upside return air inlet was still better than downside return air inlet and in-creased with the increasing of the air change rate. But the variation was slight. The characteristics of the semi mixed semi displacement ventilation were embodied.

Fig 3 shows the vertical temperature distribution with different return air duct when the radiation panels were used and the set temperature was 22℃, the outdoor temperature was 8℃. The temperature of ceiling and floor had little variation with different location of the return air duct. When the return air inlet was set upside, the temperature near the ground was higher and the operating number of the induction radiant panels had less influence on the vertical temperature distribution. So heat from the panels installed in the ceiling can more easily reach the ground. Based on the above analysis, the upside return air inlet shown better performance than the downside return air inlet.
4.2. Indoor thermal environment

Fig 4 shows the variation of dry bulb temperature, globe temperature (GT), SET* and PMV with the operating of the induction radiant panels in the condition outdoor temperature is 6 °C and indoor set temperature is 22 °C. When SET* and PMV were being calculated, the metabolism was set to 1.2 met and dressing amount was set to 0.69 clo. It can be found that GT is 1-2 °C higher than dry bulb temperature and almost the same as SET*. One hand, the accuracy of the measured data is verified. On the other hand, the indoor thermal environment satisfies the need of comfort. If one panel (door side) or two panels (door side and center) were stopped, temperature and PMV slightly decreased. When the dry bulb temperature in the center of the lab was higher than 20°C, PMV reached -0.5. The indoor comfort was very good.

Fig 5 shows the variation of dry bulb temperature, globe temperature (GT), SET* and PMV with the operating of the traditional air conditioner in the condition outdoor temperature is 8 °C and indoor set temperature is 20°C. It could be found that the parameters of indoor thermal environment fluctuated violently. The same as the induction radiant panel, GT was almost the same as SET* and varied in the range of 22-25 °C. Range of variation of the dry-bulb temperature was greater as 20-28°C. PMV was between -2 to -1.
Fig. 5. (a) indoor environmental parameters with traditional air conditioning (dry bulb temperature, black bulb temperature ambient temperature)

For purposes of comparison, when the indoor temperature was stable, the relationship between dry bulb temperature and black-bulb temperature (GT) was arranged and shown in Fig 6. △ shows the data collected when the upside return air duct was utilized and ○ shows the data with bottom return air duct. × shows the data of traditional air conditioner. From Fig 6 it can be found that with any set temperature, GT can always keep about 1.5°C higher than dry bulb temperature. Radiation effects of the panels heat the whole building envelope, such as wall and floor to make the room warmer. When the traditional air conditioner was operating, GT had little difference from the dry bulb temperature, sometimes was even lower than the dry bulb temperature. When the dry-bulb temperatures are same, induction radiant air conditioning can produce warmer indoor environment.
4.3. Vertical temperature distribution

Fig 7 shows the vertical temperature distribution with different set temperature of the induction radiant panels with the upside return air duct. When the operating number of the panels decreased from 3 to 2, ceiling and floor temperature almost had no variation. But when the number decreased to 1, Ceiling temperature decreased 4°C, temperature difference of the vertical direction increased. When the operating number kept constant, the vertical temperature difference between 0.1m to 1.1m above the floor had little difference. But when Tsp=20°C, the temperature of the area higher than 2.0m significantly decreased with the decrease of the operating number of the panels. It was the same of area higher than 1.7m with Tsp=22°C. Thus, with the set temperature increased, the vertical temperature difference also increased. However, the vertical temperature difference of the area lower than 1.7m was very small.
4.4. Horizontal temperature distribution

Fig 8 and 9 show the interior horizontal temperature distribution drawn with the average for 30 minutes when the indoor temperature was stable collected by the 18 temperature measurement points at 1.1m above ground. It can be found that the temperature of the inner wall was high. Since the windows were adjacent to the outdoor environment, the temperature of the area near windows was lowest. The temperature of the area adjacent to the door-side was also low. But the difference from the indoor maximum temperature did not exceed 1℃. When the operating panels were reduced, temperature decreased 0.5-1℃. On the other hand, due to the install position and the wind direction which pointed to door, when the traditional air conditioner was operating, the area with lowest temperature was also near the windows. Indoor temperature gradually decreased from the center to the surrounding. The highest temperature difference could reach 2.5℃.

4.5. Vertical temperature distribution with different set temperature

Conclusion

(1) The heat transfer efficiency of the upside return air inlet was better than downside return air inlet. When the upside return air inlet was utilized, the temperature difference of the vertical temperature distribution was less.

(2) In both the cases of the induction radiant panel and the traditional air conditioner, GT was almost the same as SET*. But when the induction radiant panel was operating, GT was 1.5℃ higher than the dry bulb temperature. So the induction radiant conditioning can produce better overall comfort indoor thermal environment.

(3) The higher the set temperature was, the larger the vertical temperature difference would be. But the vertical temperature difference of the area lower than 1.7m kept very small. The vertical temperature difference of the area lower than 1.1m had no variation with the decreasing of the operating panels. The heat from the panels installed in the ceiling heat can better reach the ground with the bottom return air duct.
The temperature of the area adjacent to the door-side and windows was low. But the difference from the indoor maximum temperature did not exceed 1°C. When the operating panels were reduced, temperature decreased 0.5-1°C.

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