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A STUDY OF THERMAL COMFORT ON A NOVEL RADIANT HEAT EXCHANGER BASED ON AIR-CONDITIONING UNIT

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ABSTRACT

Conventional air conditioner is considered as one of the most prevalent cooling systems over the recent decades. However, it has strong draught sensation and indoor noise. In order to avoid such drawbacks and improve the thermal comfort, a novel radiant heat exchanger based on air-conditioning unit is proposed. A series of experiments are conducted to investigate the thermal comfort of the cooling system. The results indicate that the predicted mean vote values are between -0.7 and 0.7, and the predicted percentage of dissatisfied values are less than 15%, which are all within the ranges recommended by ISO 7730 standard. The vertical temperature difference from 0.1 m to 1.1 m is approximately 1.5 °C, which is much lower than that of conventional air systems. Compared with conventional air systems, the radiant heat exchanger cooling system can improve the thermal comfort.

Keywords: radiant heat exchanger; air-conditioning unit; thermal comfort; vertical temperature difference

NONMENCLATURE

Abbreviations

PD	Percentage Dissatisfied
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RHE	Radiant Heat Exchanger

Symbols

A	Surface area (m^2)
f_{cl}	Clothing surface area factor
h_c	Convection heat transfer (W/m^2)
M	Metabolic rate (W/m^2)
$\overline{t_r}$	Comprehensive temperature of the building envelope (°C)
$\Delta t_{a,v}$	Vertical air temperature difference between head and ankle (°C)
T	Temperature (°C)
t_a	Indoor temperature (°C)
t_{cl}	Clothing surface temperature (°C)
Pa	Water vapor pressure (kPa)
W	Effective mechanical power (W/m^2)

1. INTRODUCTION

Thermal comfort is relevant to the performance and health of human in modern buildings, which has attracted public attention for a long time[1, 2]. Currently, air conditioning systems consume a great amount of energy as a result of creating comfortable environment, while human still experience discomfort [3]. For instance, the air conditioner cooling system may cause strong draught sensation and dry-eye discomfort when the air movement is too strong[4].

Radiant cooling air-conditioning system has been a popular research hotspot for its simple structure, high energy efficiency and low annual operating cost [5]. Many studies have demonstrated that the directly radiant heat exchanger could improve the thermal comfort levels and mitigate local discomfort compared with common convective air conditioning systems. Zhao and Liu [6] investigated the subjective comfort of radiant cooling floor in some large buildings. The results

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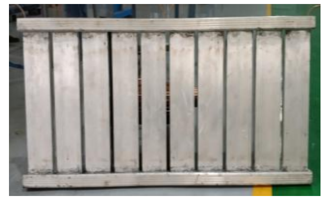
showed that the energy efficiency and thermal comfort of the radiant cooling system are better than those of the all-air system. Imanari et al. [7] conducted experiments with radiant ceiling panels of cooling system in a resident room and concluded that humans feel more comfortable of this system than the all-air system. The existing directly radiant heat exchanger also has drawbacks, for example, ceiling and floor radiant cooling systems need to control the surface temperature higher than dew temperature or set ventilation device in order to prevent condensation water[8, 9]. Song et al. [10] studied the combination of a radiant floor cooling system and dehumidified ventilation system in the hot and humid season, which was demonstrated to solve the condensation problem successfully.

In this paper, a novel radiant heat exchanger (RHE) is presented. Experiments are conducted to evaluate the indoor thermal comfort of the RHE cooling system. The variations of the predicted mean vote (PMV) values and the predicted percentage of dissatisfied (PPD) values are analyzed with different indoor temperatures. Besides, the thermal comfort of the RHE cooling system and traditional air conditioner is also compared.

2. EXPERIMENTATIONS

2.1 Radiant heat exchanger

The schematic of the RHE is shown in Fig.1. The dimensions of the heat exchanger is 1.6 m×0.11 m× 0.65 m (L×W×H). The heat exchanger includes two aluminum-alloy-column panels, copper pipes and fins, water-containing plate and water stored for thermal energy storage. The front of heat exchanger is made into plane shape, the longitudinal rectangular fins are arrayed on the backside of the front panel and both sides of the back panel. The length, width and thickness of the fins are 600 mm, 20 mm and 1 mm separately, and the space between the fins is 10 mm. The fins and panel constitute a series of air passages for enhancement of the natural convection heat transfer. The total length of copper pipes is 50 m, which are divided into four parallel paths. The S-shaped copper pipes are embedded in the panels and the diameters of the inlet and the outlet pipes are 6.35 mm and 9.52 mm separately, owing to the state of refrigerant changed from liquid to gas. The water-containing plate is used to collect the condensation water of the RHE surface during the cooling period. The gaps between the aluminum-alloy-column panels and the copper pipes are filled with water as thermal storage medium to supply energy during defrosting period in winter, however, it has thermal inertia in summer cooling conditions.


(a) front


(b) back

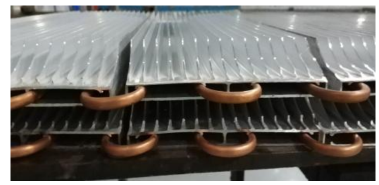

(c) profile

Fig 1 The schematic of the RHE

2.2 Experimental setup and point measurement

As shown in Fig.2, the experimental setup consists of an outdoor-environmental chamber, an indoor-environmental chamber and an air-conditioning unit with RHE. The sizes of the indoor and outdoor environmental chambers are identical, which are 4.4 m ×4.4 m×3 m (L×W×H), respectively. Air temperature and relative humidity of the outdoor-environmental chamber can be maintained within -20 ^{o}C ~ 60 ^{o}C and 20% ~ 90%, respectively, which are controlled by an independent air conditioning system. Correspondingly, air temperature and relative humidity of the indoor-environmental chamber can be maintained within 10 ^{o}C ~ 50 ^{o}C and 20% ~ 90%, respectively. In order to avoid the interference from forced air convection, a test room is built with 3.5 m×3.5 m×3 m (L×W×H) steel plate in the indoor-environmental chamber.

The experimental setup of the RHE is comprised of an inverter-driven rotor compressor, a condenser, a subcooler, a four-way valve, an electronic expansion valve, a gas-liquid separator and a radiant heat exchanger. The refrigerant is compressed and fed into the condenser, then passed through the electronic expansion valve and evaporated by the RHE, and finally flowed back into the compressor. R410A is chosen as the refrigerant of this cooling system for its environmental friendliness. The nominal cooling capacity and the nominal input electric power of the compressor are 3500 W and 975 W, respectively.

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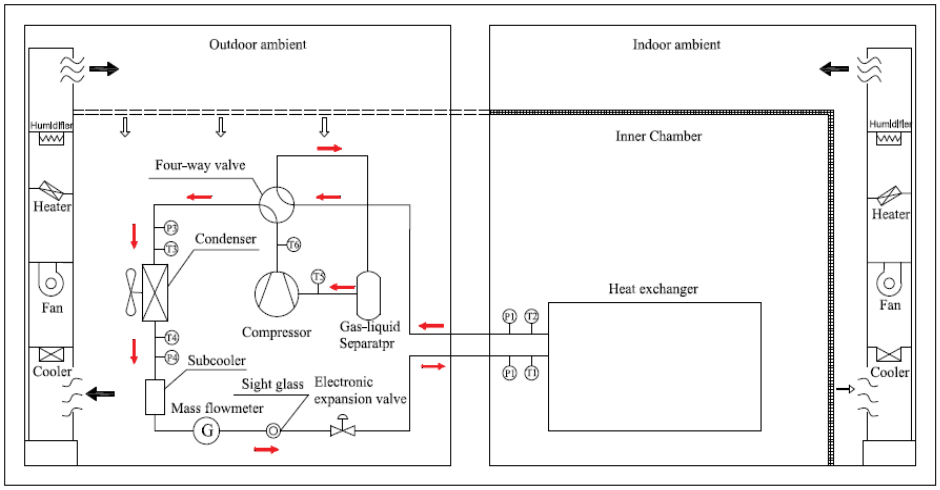

Fig 2 Schematic of experimental setup

The surface temperatures of the vertical walls, floor, ceiling in the test room are measured. Fig.3 shows the layout of the temperature measuring points in the test room. The measuring point at the height of 1.1 m on the center line is defined as the reference temperature point. The humidity sensor is also set at this place to monitor the air relative humidity of the test room.

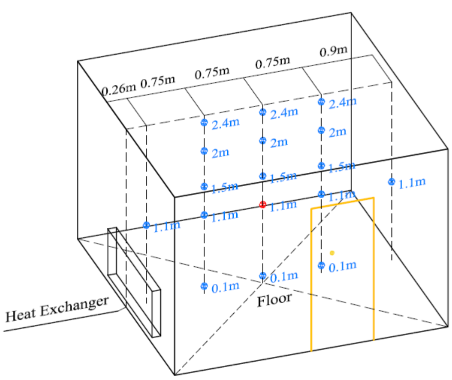

Fig 3 Temperature sensors distribution in the test room

3. ANALYTICAL MODEL

3.1 PMV model

According to personal and environmental variables, Fanger's PMV model can assess the thermal comfort of near-sedentary and stationary occupants accurately [11]. The PMV is defined by Fanger [12] as:

$$PMV=[0.303\exp(-0.036M)+0.0275]\times\{M-W-3.05[5.733-0.007\times(M-W)-P_a]-0.42(M-W-58.2)-0.0173\times M(5.867-P_a)-0.0014M(34-t_a)-3.96\times10^{-8}\times f_{cl}\times[(t_{cl}+273)^4-(\overline{t_r}+273)^4]-f_{cl}h_c(t_{cl}-t_a)\}$$

$$\overline{t_r}=\frac{\sum_{i=1}^{6}A_iT_i}{\sum_{i=1}^{6}A_i}$$

3.2 PPD model

PPD predicts the percentage of thermally dissatisfied people, which was also proposed by Fanger [12]:

$$PPD=100-95\exp[-(0.03353PMV^4+0.2179PMV^2)]$$

PPD calculation may be more trustable than PMV since individual votes show scatter due to human factors [13]. The classification of thermal environment is listed in Table 1.

3.3 PD model

Excessive vertical air temperature difference between the head and ankle will lead to discomfort for humans. The ANSI/ASHRAE Standard 55 [14] requires that the vertical temperature difference between the head and ankle levels should not exceed 3 ^{o}C. These level heights are 0.1 m and 1.1 m for seated occupants, and 0.1 m and 1.7 m for standing occupants, respectively. Moreover, the ISO Standard 7730 [15] uses percentage dissatisfied (PD) as an evaluation index of vertical air temperature difference, which can be divided into three categories, as illustrated in Table 1. It can be calculated by:

$$PD=\frac{100}{1+\exp(5.76-0.856\times\Delta t_{a,v})}$$

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Table 1 The classification of thermal environment

category	Systemic heat		Local thermal discomfort
	PPD/%	PMV	PD/%
A	<6	-0.2<PMV<+0.2	<3
B	<10	-0.5<PMV<+0.5	<5
C	<15	-0.7<PMV<+0.7	<10

4. RESULTS AND DISCUSSION

4.1 PMV effects of indoor temperature

The relationships between PMV and indoor temperature in different evaporation temperature during the testing period are presented in Fig.4. It can be inferred that all the PMV values are between -0.7 and 0.7, while 37.5% of the values are between -0.2 and 0.2 and 75% of the values are between -0.5 and 0.5. Hence, it can be concluded that the RHE cooling system can provides thermal comfort conditions for human body. Meanwhile, as the indoor temperature increases, the PMV value trends to increase as well, which is the result of the weak natural convection and radiation heat transfer of the heat exchanger. It is indicated that the PMV values are affected by indoor temperature.

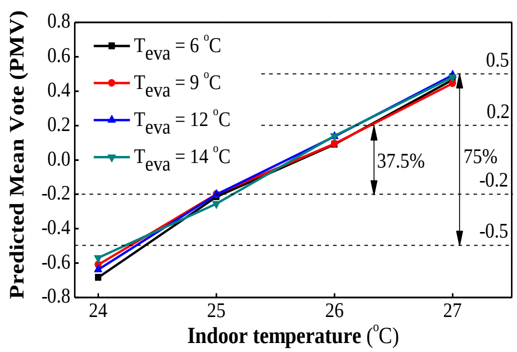

Fig 4 The relationships between PMV and indoor temperature

4.2 PPD effects of indoor temperature

Fig.5 depicts the variation of PPD with various indoor temperature during the cooling period. The result reveals that the PPD values are higher when the indoor temperature is 24 °C and 27 °C, which denotes that human will feel more comfortable if the indoor temperature is between 25 °C and 26 °C. It indicates that all the PPD values are less than 15%, while 43.8% of the values vary from 0% to 6% and 75% of the values vary from 0% to 10%. In addition, no significant correlation is found between the overall thermal sensation and evaporation temperature in RHE cooling system, providing that the indoor temperature remains constant. It is demonstrated that this air-conditioning unit with RHE can provide considerable indoor thermal comfort under actual operating conditions.

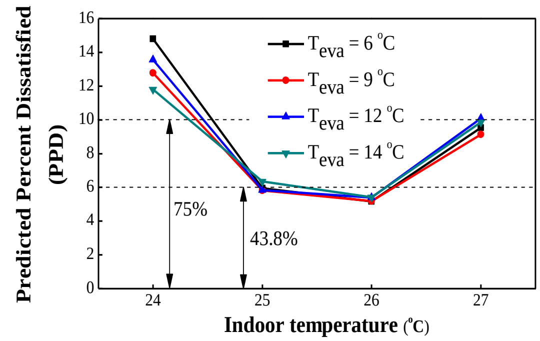

Fig 5 The relationships between PPD and indoor temperature

4.3 Comparison with conventional air systems on temperature distribution

Compared to conventional air systems which depend on convection only, the RHE cooling system provides cooling by the combination of radiation and natural convection. Fig.6 describes the comparison between the RHE cooling system and conventional air systems for the case of the indoor thermal comfort. The temperature difference from 0.1 m to 1.1 m is approximately 1.5 °C, which does not exceed upper limit (3 °C) regulated by the ISO 7730 standard. On the contrary, the vertical temperature difference from 0.1 m to 1.1m varies from 1.83 °C to 4.93 °C for conventional air systems [16], which is higher than the proposed RHE cooling system.

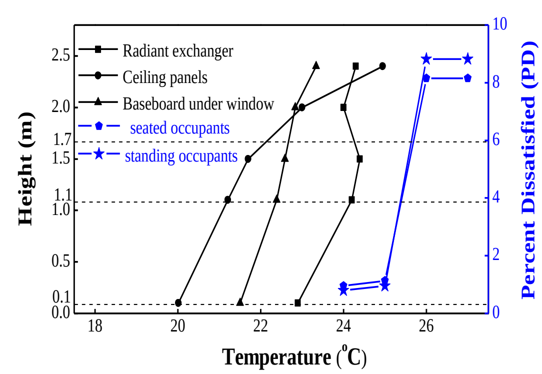

Fig 6 Vertical air temperature differences for different cooling system and PD values of RHE cooling system

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In addition, under the indoor air temperature varies from 24 ^{o}C to 27 ^{o}C of the RHE cooling system, the PD values range from 0.95% to 8.15% for seated occupants. Correspondingly, the PD values range from 0.8% to 8.82% for standing occupants. It is noticeable that the indoor thermal comfort can meet the level of Class C, which illustrates that the RHE cooling system can provide an ideal thermal comfort and mitigate cold draught. Besides, it allows the dew condensation behavior on RHE surface and has the characteristic of independent indoor dehumidification.

5. CONCLUSION

In this study, a RHE based on air-conditioning unit is proposed. The thermal comfort performance of the heat exchanger is experimentally conducted. The conclusions are as follows:

(a) During the testing period, all the PMV values with different indoor temperature are between -0.7 and 0.7, which indicate that the heat exchanger can supply acceptable thermal comfort.

(b) In the range of 0% to 6%, the indoor PPD values of the heat exchanger accounts for 43.8%, while it is 75% between 0% and 10% under different reference temperature, which can meet the standard recommended value.

(c) Comparative analysis on indoor temperature distribution of this system shows that the vertical temperature difference between head and ankle is less than the conventional air systems.

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