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The effect of diffuse ceiling ventilation air supply on human thermal comfort under radiant asymmetry

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Abstract. Sidewall radiant heating creates a non-uniform thermal environment. In office buildings, it is important to know how to supply fresh air to reduce radiant asymmetry without causing draft. As a solution, diffuse ceiling ventilation (DCV) is used to supply fresh air into a sidewall radiant heated room. 20 subjects (10 males and 10 females) were recruited and subjective assessments were obtained. The results show that under the influence of sidewall radiant heating, there are differences in the subjects' requirements for airflow and wall temperature on both body sides. Skin temperature and thermal sensation of the same body parts decrease differently when the subjects move away from the radiant heating panels, especially in forearms, shanks and feet. DCV airflow with low supply momentum interacts with thermal plume formed by radiant heating panels.

1 Introduction

In the early stages of the research on the effect of radiation asymmetry on human thermal comfort, Fanger proposed the asymmetric radiation temperature and gave the relationship between the asymmetric radiation temperature of the warm wall and the predicted dissatisfaction rate (PD) and the design limit of the asymmetric radiation temperature, i.e., the maximum limit of the radiation asymmetry temperature of the warm wall at PPD < 5% is 23°C [1].
Subsequently, the effect of asymmetric radiation on human thermal comfort has been studied by a large number of national and international scholars. McNall et al. studied the thermal comfort of subjects under asymmetric radiation and showed that the overall thermal sensation of subjects in an asymmetric radiation environment was neutral and that much fewer subjects felt overall thermal comfort than in an environment without asymmetric radiation [2]. Yen et al. demonstrated that human thermal sensation increased with the increase in asymmetric radiation temperature. Hou and Wang studied the human thermal response to radiation asymmetry caused by cold radiation from external windows and showed that the further the distance from the external window, the higher the skin temperature, thermal sensation votes and thermal comfort votes [3-4]. Zhou et al. examined the thermal comfort effects of different exposure times under different radiation asymmetries and found that different radiation asymmetries led to different subjective responses [5]. In conclusion, it can be seen that both the non-uniform indoor thermal environment and the relative distance between the indoor occupants and the source of heat and cold radiation affect the thermal sensation and thermal comfort of the occupants.

However, most studies have not focused on how to optimize the delivery of fresh air in office buildings with sidewall radiant heating to avoid local drafts and eliminate radiant heat asymmetry. Hence, in the present study, the airflow distribution method (DCV) is used in the sidewall radiant heating room to improve the thermal comfort of the occupants and supply fresh air into the room.

2 Methods

2.1 Thermal environment chamber

This experiment was conducted in the thermal environment chamber at Xi'an University of Architecture and Technology, as shown in Figures 1 and 2. The chamber consists of a plenum, a porous ceiling, a ventilation chamber, a porous exhaust floor and an exhaust chamber, with heating radiation panels located on the south wall. The diameter of the porous ceiling holes is 6mm, uniformly open and with a porosity of 0.38%. The dimensions of the ventilation room are 3.8 m × 3.8 m × 3.1 m. The air change rate is 5 ACH. Indoor air temperature and humidity is around 20°C and 45% with an accuracy of within ± 0.5°C and ± 5%.

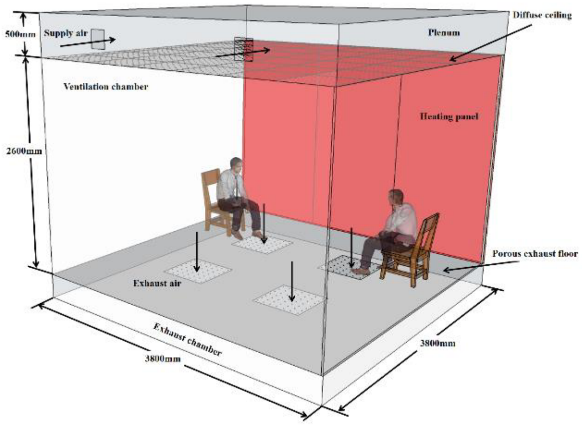

Fig. 1. Schematic diagram of the thermal environment chamber.

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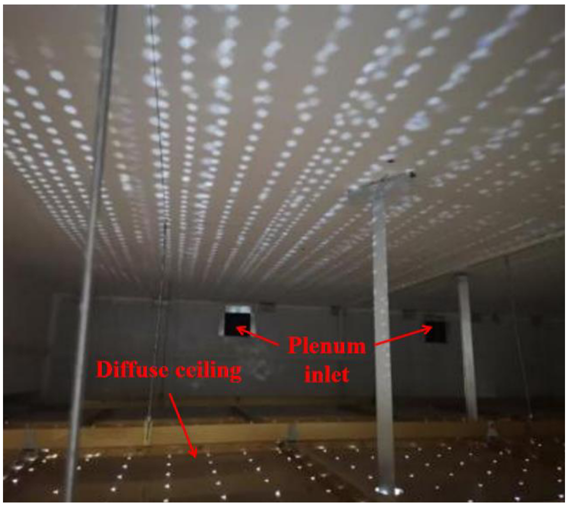

Fig. 1. Plenum chamber.

2.2 Parameters and experimental instruments

The thermal environment of the chamber was measured. The main parameters and the experimental instruments are shown in Table 1. Temperature, humidity and carbon dioxide meters were placed at 0.1, 0.6 and 1.1 m in the center of the chamber. The global thermometer was placed at the height of 0.6 m in the central. Three anemometers were placed at 0.2 m on the side of the subject's body at heights of 0.1 m, 0.6 m and 1.1 m, respectively.

Table 1. Main parameters and measuring instruments.

Parameter	Type	Range	Accuracy
Air temperature	RTR-576, T&D Corporation, Matsumoto, Japan	0~55°C 10~90% RH 0~9999 ppm	±0.5°C 5% RH
Air humidity			
CO2 concentration			
Globe temperature	HQZY-1, Beijing Tianjian Huayi Technology Development Co., Ltd., Beijing, China	-20~80°C	± 0.3°C
Air velocity	Swema SWA03, SWEMA AB, Stockholm, Sweden	0.05~3.0 m/s	± 0.03 m/s (0.05-1.00 m/s) ± 3% of reading (1.00-3.00 m/s)
Skin temperature	iButton DS1921H, Maxim Integrated, San Jose, California, USA	-40~100°C	± 0.125°C

2.3 Subjects and procedure

Twenty subjects (10 males and 10 females) were recruited for this experiment. Anthropometric data of the 20 participants are shown in Table 5. Subjects wore uniform clothes with a thermal resistance of 1.0 clo (i.e., long pants and sweater). Participants were instructed to refrain from exercising for at least one hour before the start of the trials. They had a metabolic rate of 1.0 met during the trials.

Table 2. Anthropometric data of the participants.

Gender	Body Surface Area (BSA, m^2)	Age (years)	Height (cm)	Weight (kg)	Body Mass Index (BMI, kg/m^2)
Males	1.9 ± 0.2	24.1 ± 1.9	175.9 ± 7.2	70.7 ± 10.6	22.8 ± 2.6
Females	1.6 ± 0.1	22.0 ± 1.1	161.8 ± 4.1	54.3 ± 5.2	20.8 ± 2.4

The positions were divided into three positions N (1.0 m), M (2.0 m) and F (3.0 m) according to the distance from the heating radiation panel, with asymmetric radiation temperatures ($\triangle T_{pr}$) of 3.8℃, 6.0℃ and 9.0℃， respectively. The subjects were given 20 minutes before the formal test to adjust to the thermal environment in the chamber and learn how to vote. After spending 30 minutes in each location, the subjects were given 10 minutes to adjust to the thermal environment of the chamber. Subjects were required to complete a subjective questionnaire every 5 minutes. The experimental procedure is shown in Figure 3.

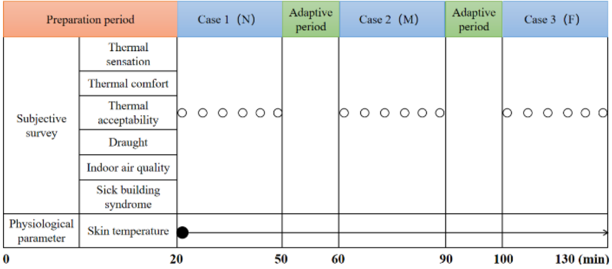

Fig. 3. Experimental procedure.

3 Results

The data were analyzed and plotted using Origin 2018, and the S-W test (Shapiro-Wilk's test) was used to infer whether the samples obeyed a normal distribution. The chi-square test was performed when the overall subjective voting results of the subjects obeyed a normal distribution. The Levene test was used to test whether the overall variance of the sample was significantly different. One-way ANOVA was used when the overall variance of the sample was not significantly different. If the entire sample did not obey normality, or if the overall variance of the sample was significantly different when a chi-square test was performed, a nonparametric test, i.e., Friedman's analysis of variance with multiple independent nonparametric tests would be used. Significant differences are marked in graphs: * indicates $p < 0.05$; ** indicates $p < 0.01$; *** indicates $p < 0.001$.

3.1 Objective environmental parameters

The air velocity at the opposite sidewall of the radiation heating panel was higher than that at the heating panel (south wall). And the air velocity at the north wall was 2 to 3 times that at the south wall. This indicated that a large-scale circulating airflow from the radiant heating panels to its opposite sidewall was formed in the radiant asymmetric heating condition. The details of the designed conditions and objective parameters measured in the experiment are shown in Table 3.

Table 3. Design condition and objective measurement.

	Design condition			
	$\triangle T_{pr}$	T_a	RH	CO_2
N	9.0℃	20℃	45%	<1000 ppm
M	6.0℃			
F	3.8℃			
	Objective measurement			
	$\triangle T_{pr}$	T_a	RH	CO_2
N	8.3℃	20.8±0.2℃	45.0±3.2	595.5±27.1 ppm
M	5.8℃			
F	3.9℃			

3.2 Skin temperature

The local and average skin temperatures of the subjects were influenced by asymmetric radiation, and local and mean skin temperatures differed between the two sides of the subject's body, as shown in Figures 4 and 5.

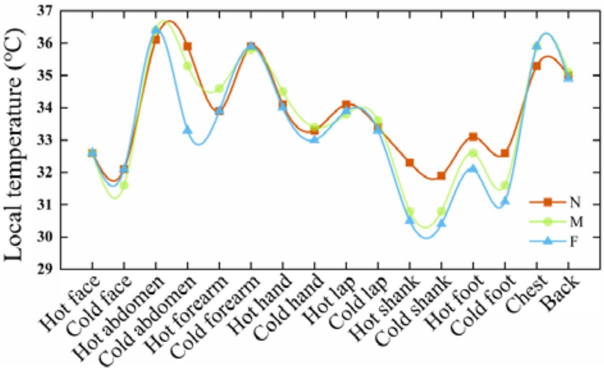

Fig. 4. Local skin temperature.

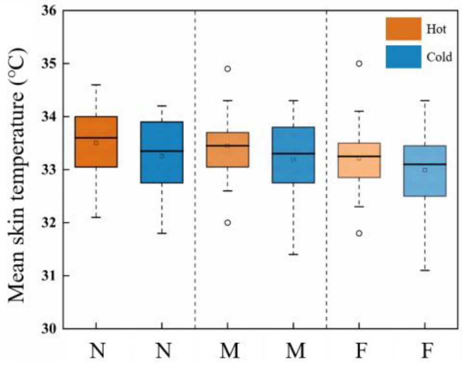

Fig. 5. Mean skin temperature.

Statistical analysis showed no significant differences in local skin temperatures when subjects were in different positions, and skin temperatures of the lower legs, feet and abdomen near the north wall were significantly lower when moving away from the radiant heating panels. When the local skin temperature on the side of the subject near the south wall was higher than the local skin temperature on the side away from the south wall, the magnitude of the difference between the two increased as the subject's distance from the south wall increased. The results of the statistical analysis showed that there was no significant difference in the mean skin temperature between the left and right sides of the subjects at the same location, nor was there a significant difference in the mean skin temperature on the same side at different locations. The average skin temperature on the same side of the subject decreased with increasing distance from the radiant heating panels, and the average skin temperature decreased more on the side close to the radiant heating panels. The lower limit of the average skin temperature on the side away from the radiant heating panel was much lower than that on the side close to the heating panels, and the difference in the average skin temperature between the two sides increases as the distance from the heating panel increased.

3.3 Thermal sensation

It can be seen in Figures 6 and 7 the change in subject position had a greater effect on their overall and local heat sensation. The overall thermal sensation of the subjects decreased significantly ($p < 0.01$) with the subject moving away from the radiant heating panels, especially in position F where the subjects' overall thermal sensations tended to be slightly cool. There was a significant reduction in thermal sensation in the face, hands and lower legs when the subjects were away from the radiation heating panels. And the lowest value decreased significantly, with significant differences in local heat sensation in the face, hands and lower legs at N and F ($p < 0.001$).

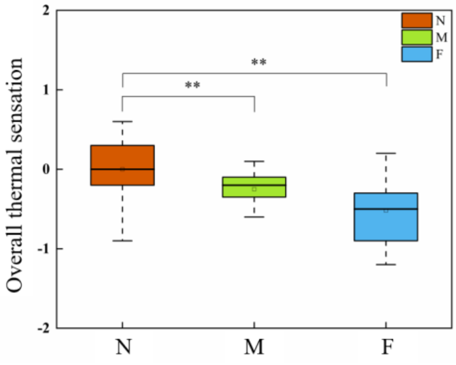

Fig. 6. Overall thermal sensation.

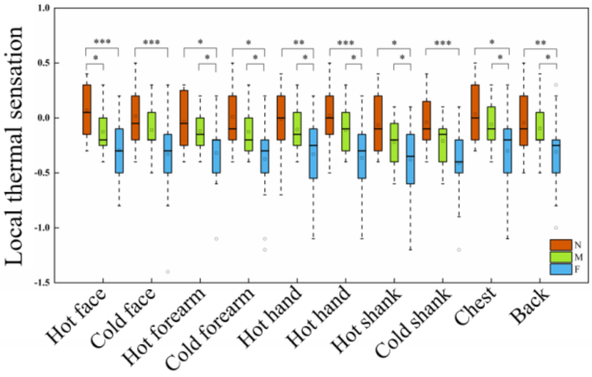

Fig. 7. Local thermal sensation.

3.4 Thermal comfort

There was a highly significant difference ($p < 0.001$) between subjects' voting results for thermal comfort at N and F, with their thermal comfort being the worst when they were at F. It can be seen from Figure 8 that the subjects' thermal comfort voting results were not lower when the subjects were further away from the radiant heating panels, the subjects' thermal comfort voting values were higher at M than at N.

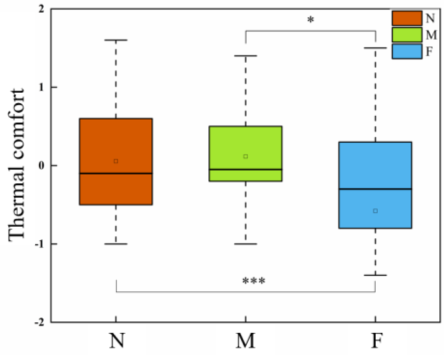

Fig. 8. Thermal comfort.

3.5 Radiation asymmetry

As subjects moved away from the radiant heating panels, the percentage of subjects who wanted the north and south walls to be warmer increased. And more subjects wanted to raise the temperature of the north wall than the south wall, by a ratio of nearly 2:1. The percentage of subjects who wanted the temperature of the north wall to increase was 10% higher at F than at the rest of the locations. When subjects were at N, the percentage of subjects who wanted the temperature of the radiant heating panel to decrease was 5% higher compared to the other locations.

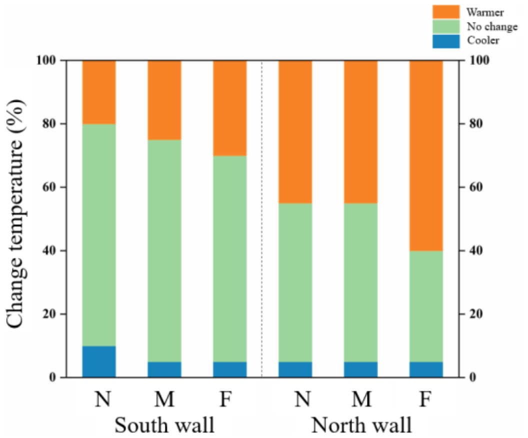

Fig. 9. Change temperature.

4 Conclusion

The heat plume formed by the sidewall radiant heating panels had a large buoyancy force and the DCV air supply airflow had a low air supply momentum, so the fresh air airflow was fully mixed with the thermal buoyancy force. Eventually, a circulating airflow from the radiant heating panels to the opposite wall was created in the room agreed with the results of Lestinen's study [6]. Radiation asymmetry had a large impact on human thermal comfort. Large differences in skin temperature and thermal sensation between the two sides of the subject's body, resulting in differences in the subject's temperature requirements for the radiant heating panels on both sides of the body. As the subject moved away from the radiant heating panels, the skin temperature and thermal sensation votes of the same body parts of the subjects gradually decreased, but the decrease and the lowest value of the skin temperature and thermal sensation votes differed significantly for different parts of the subjects. Males and females had different preferences for the temperature of radiant heating panels, with males being more accepting of a radiant asymmetric thermal environment.

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