

Thermal response test analysis of adults and preschoolers under radiant floor heating environment in a hot-summer and cold-winter area

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Abstract. The subjective and objective thermal comfort evaluations of adults and preschoolers in radiant floor heating rooms in a hot-summer and cold-winter area are tested in this article, and the thermal response of the two groups of subjects are analysed using a differential analysis method. The thermal response characteristics of subjects wearing winter clothing with a thermal resistance of 1.02 clo and maintaining a sitting posture were studied at different locations in the office building and different indoor temperatures by combining the characteristics of hot-summer and cold-winter area and the characteristics of office buildings. The results show that when the indoor temperature varies, there was a significant difference in the local skin temperature of the calf of the two groups of subjects ($P < 0.05$). Preschoolers have a more intense overall thermal sensation vote than adults due to the difference in metabolic rate. Different groups of people's overall thermal sensation vote were linearly correlated. The overall thermal sensation vote of the subjects is linearly related to the indoor operative temperature. The PMV-PPD model is used as the thermal sensation evaluation standard, and there is a considerable difference between the subjective appraisal of preschoolers' thermal sensations. The PMV-PPD model is not suitable for preschoolers.

1 Introduction

Winter is wet and chilly in hot-summer and cold-winter, and the inner thermal and humid atmosphere is harsh, however, there is no central heating. To achieve a higher quality of life, people in this area demand heating to fulfil the parameters of an acceptable temperature gradient, not dry and with no draught. Radiant floor heating is currently widely utilized for space heating in China [1], and it is regarded to offer superior thermal comfort [2] [3]. According to Gao [4], the homogeneity and thermal comfort of the indoor temperature field distribution of radiant floor heating are preferable to those of fan coil heating. Scholars studied the thermal response of the human body to the asymmetric radiation and uneven indoor thermal environment created by the radiant floor, and the cold radiation of the external wall and the west window during the winter. Wang et al. [5] noticed that there are distinctions in humans' local thermal sensation and thermal comfort whether they are working in the same or different conditions, and the calf has seen the most significant distinction. Zhang [6] believed that the subjects' overall thermal sensation and thermal comfort are influenced by the most uncomfortable part of the local area; Wang et al. [7] revealed that the cold radiation of the external window may cause the local skin temperature to drop, especially in the calf and back; Schellen et al. [8] investigated

gender variations in human physiology and thermal comfort under heterogeneous environmental conditions. The findings demonstrate that the overall average thermal sensation vote differs considerably from the PMV. Furthermore, women are more uncomfortable and dissatisfied than males; The thermal sensation of the arm and the skin temperature influence the thermal sensation in women; Through literature survey, it is found that children's perceptions and comprehension of thermal comfort have rarely been researched, although children's growth and well-being require a comfortable environment. The purpose of this paper is to investigate the subjective and objective thermal comfort evaluation methods of 16 adults and preschoolers in the situation of low-temperature radiant floor heating and to apply different analysis methods to analyze the subjects' thermal responses, and analyze the difference and connection between preschoolers' and adults' thermal responses.

2 Experiment

The air source heat pump is used as the heat source, and the floor radiation is used as the asymmetric radiation terminal; the water supply temperature of the heat source is set at 35 °C, and the interior design temperature is 22 °C. During the study, 16 subjects were separated into four groups: one male and one female

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school-aged youngster, and one male and one female adult, each in a sitting state and wearing 1.02 clo winter clothing is allocated to each condition, shown in Table 1. Tables 2 provide essential information about the two groups of subjects.

Table 1. Experimental condition.

Condi tions	Air temperature (°C)	Relative humidity (%)	Distance from external windows (m)
1	21.39	38.3	1.2
2	22.60	38.3	3.6
3	22.60	40.6	1.2
4	23.90	40.6	3.6

Table 2. Basic information of two types of subjects.

Subje cts	Gender	Age	Height H(cm)	Weight W(Kg)
Presch oolers	Male	4.25±0.50	116.33±2.72	21.35±0.90
	Female	4.00±0.82	117.63±3.29	20.90±2.25
Adult	Male	23.5±1.00	176.25±4.86	73.55±6.78
	Female	24.25±1.50	163.25±8.06	54.40±4.36

The subjective study of human psychological thermal response includes local skin temperature. On the human body, local temperature measurement sites include the forehead, back, abdomen, arm, hand, and calf. The ASHRAE seven-point [9] continuous scale was used for local and overall thermal sensation.

The preschoolers were taught in kindergarten mode before the experiment began since sensation and perceptual issues were strictly dependent on the educator's method. The preschoolers' questionnaire is represented by an image picture, as illustrated in Figure 1. The experiment lasted 90 minutes, and the skin temperature was measured and recorded every 15min with an infrared temperature measuring gun; meanwhile, a questionnaire was submitted every 15min. System sensor parameters in the experimental room are shown in Table 3.



Fig. 1. Image of preschoolers' thermal sensation.

Table 3. Physical parameters of system sensor

Type	Temperature and humidity sensor	Infrared temperature measuring gun	Anemograph
Measuring range	-40~+80°C 0~100%RH	-30~350°C	0~5m/s
Measurement error	±0.3°C ±2%RH	±1.5°C	±0.02m/s
Resolution	0.1°C 0.1%RH	0.1°C	0.01m/s
Maker	RENKE	TESTO-830-S1	Pushington

3.1 Local skin temperature

Figure 2 indicates that skin temperatures differ at different places under the same conditions; local skin temperatures for both types of subjects were maintained between 29 and 35 °C; abdomen and back temperatures were relatively higher for both types of subjects under different conditions.

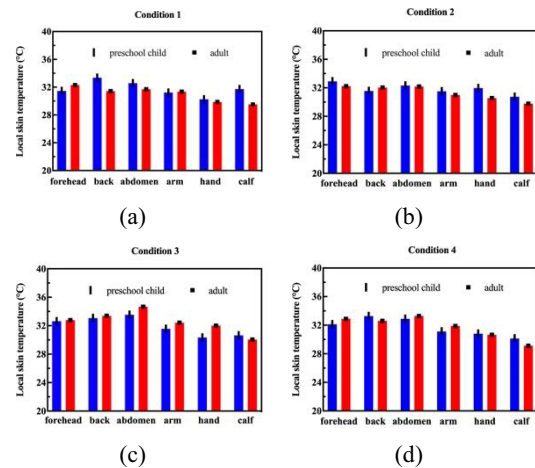


Fig. 2. Changes of local skin temperature under four conditions.

When conditions 1 and 3 are compared to conditions 2 and 4, it is shown that the local skin temperature in conditions 1 and 3 changes more than that in conditions 2 and 4. Because conditions 1 and 3 are adjacent to the west window, the west window has a large-area glass construction (WWR77%) that conducts convection and radiation heat exchange with the outdoors, resulting in an uneven air temperature distribution near the window. Then the subject's local skin surface conducts radiant heat exchange with the west window glass and convective heat exchange with the surrounding air, causing the local skin temperatures in conditions 1 and 3 to differ significantly.

Except for significant differences in the skin temperature of calf between preschoolers and adults in conditions 1 and 4, and significant differences in the skin temperature of hand in condition 3, the local skin temperatures of the two types of subjects were not significantly different, as shown in Table 4. This indicates that calf sensitivity to floor radiation varied between the two groups of subjects, with preschoolers being closer to the ground.

Table 4. Paired T-test sig. (two-tailed) values of local skin temperature.

Condi tions	Foreh ead	Back	Abdo men	Arm	Hand	Calf
1	0.150	0.057	0.218	0.429	0.727	0.000
	>0.05	>0.05	>0.05	>0.05	>0.05	<0.05
2	0.166	0.543	0.769	0.371	0.088	0.259
	>0.05	>0.05	>0.05	>0.05	>0.05	>0.05
3	0.785	0.704	0.060	0.062	0.003	0.304
	>0.05	>0.05	>0.05	>0.05	<0.05	>0.05
4	0.126	0.242	0.405	0.268	0.651	0.042
	>0.05	>0.05	>0.05	>0.05	>0.05	<0.05

3 Skin temperature comparison

3.2 Mean skin temperature

The mean skin temperature is a weighted average of the skin temperatures of different body parts, with the weighting factor determined by the area size of the part. The 6-point thermometry method [10] uses six different locations: the forehead, back, abdomen, arm, hand, and calf. The formula for estimating the average skin temperature is summarized below:

$$T_{skin} = 0.07T_{forehead} + 0.26T_{back} + 0.35T_{abdomen} + 0.14T_{arm} + 0.05T_{hand} + 0.13T_{calf} \quad (1)$$

where T_{skin} is the mean skin temperature ($^{\circ}\text{C}$); $T_{forehead}$, T_{back} , $T_{abdomen}$, T_{arm} , T_{hand} , and T_{calf} are the forehead, back, abdomen, arm, hand, and calf skin surface temperatures, respectively ($^{\circ}\text{C}$).

The mean skin temperature was lower in conditions 1 and 2 than in conditions 3 and 4; in conditions 1 and 2, preschoolers had a higher mean skin temperature than adults. Whereas, in condition 3, adults had a higher mean skin temperature than preschoolers in Figure 3.

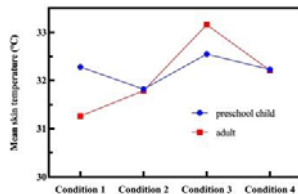


Fig. 3. Changes of mean skin temperature under four conditions.

The analysis results indicate that conditions 1 and 3 are disturbed by cold radiation from external windows and walls, resulting in a significant effect of asymmetric radiation on mean skin temperature. However, there was no significant difference in mean skin temperature between the two groups of subjects under four situations ($P > 0.05$) in Table 5.

Table 5. Paired T-test sig. (two-tailed) values of mean skin temperature.

Conditions	Subjects	Mean skin temperature
1	Preschoolers-Adults	0.082
		>0.05
2	Preschoolers-Adults	0.604
		>0.05
3	Preschoolers-Adults	0.166
		>0.05
4	Preschoolers-Adults	0.975
		>0.05

4 Discussion

4.1 Relationship between overall thermal sensation vote and mean skin temperature

The change in human skin temperature has a statistical link with the evaluation of the thermal sensation of the subjects, according to EN ISO7730 [11]. Zhang et al. [12] proposed that the mean skin temperature has a good linear association with the overall thermal sensation. When the human skin temperature is between 29 and 34 $^{\circ}\text{C}$. When the mean skin temperature is less than the thermoneutral skin

temperature of 3 $^{\circ}\text{C}$ to more than the thermoneutral skin temperature of 1 $^{\circ}\text{C}$, Fiala, et al. [13] found that the mean skin temperature has a good linear association with the overall thermal sensation, when the mean skin temperature is 3 $^{\circ}\text{C}$ lower than the thermoneutral skin temperature to 1 $^{\circ}\text{C}$ higher than the thermoneutral temperature. There is a high primary linear association between the overall thermal sensation vote in preschoolers and adults, and the linear regression equation is shown in Figure 4.

The mean skin temperature for preschoolers was 31.06 $^{\circ}\text{C}$ and 31.33 $^{\circ}\text{C}$ for adults when the overall thermal sensation vote was "neutral". The difference in the overall thermal sensation vote between the two types of subjects became more significant as the mean skin temperature exceeded 31 $^{\circ}\text{C}$; when the mean skin temperature was the same, the overall thermal sensation vote of preschoolers was "warm" compared to that of adults.

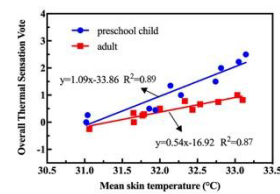


Fig. 4. Changes of overall thermal sensation vote with mean skin temperature.

4.2 The relationship between overall thermal sensation vote and thermal indoor operative temperature

The overall thermal sensation vote of subjects had a strong linear relationship with the indoor operative temperature in Figure 5, and the overall thermal sensation vote increased as the indoor operative temperature rose. The difference in the overall thermal sensation vote between the two groups of subjects became more significant as the indoor operative temperature exceeded 22.1 $^{\circ}\text{C}$; when the operative temperatures were the same, preschoolers' overall thermal sensation vote was more "warm" than that of adults.

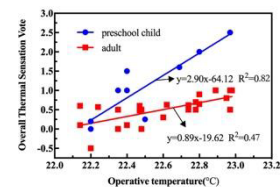


Fig. 5. Changes of overall thermal sensation vote with operative temperature.

4.3 Relationship between overall thermal sensation and measured PMV

Professor Fanger's PMV-PPD model and the overall thermal sensation vote are compared in this paper. The difference between measured PMV and overall thermal sensation vote ranged from 0.27 ~ 0.94 for adults and 0.77 ~ 2.33 for preschoolers in Table 6. Due to the significant bias of the measured PMV model as a

criterion for thermal sensation evaluation in preschoolers, the measured PMV-PPD model is not suitable for them. The PMV-PPD model was created by observing moderately sedentary students and adults in a climate chamber, while J. van Hoof [14] has pointed out that Fanger's PMV-PPD model applies to healthy adults but cannot be applied to preschoolers, the elderly, or the disabled without modification. This paper's finding is in agreement with J. van Hoof's.

Table 6. Difference between measured PMV and overall thermal sensation vote.

Condi tions	Subjects	Measured PMV	Overall thermal sensation vote	Difference
1	Adults	-0.273	0.67	-0.94
	Preschool ers	-0.273	1.17	-1.44
2	Adults	-0.273	0.00	-0.27
	Preschool ers	-0.273	0.500	-0.77
3	Adults	-0.162	0.500	-0.66
	Preschool ers	-0.162	1.167	-1.33
4	Adults	-0.162	0.500	-0.66
	Preschool ers	-0.162	2.167	-2.33

5 Summary

The following conclusions were drawn after comparing the relationship between the skin temperature, the subjective thermal response of adults and preschoolers as well as the questionnaire and the actual results of the data collection system under four conditions with radiant floor heating:

(1) There is a substantial difference in the skin temperature of calf between preschoolers and adults in conditions 1 and 4, indicating that the sensitivity of the calf to radiant floor heating differs between the two groups of subjects and that preschoolers are closer to the floor. There is no significant difference in mean skin temperature between the two groups of subjects under four conditions ($P > 0.05$), but the asymmetric radiation environment influences skin temperature.

(2) The cold radiation of the external window may cause the local skin temperature to drop, as the result of the local skin temperature in conditions 1 and 3 changing more than that in conditions 2 and 4.

(3) The overall thermal sensation vote of adults and preschoolers and mean skin temperature, as well as the indoor operative temperature, has a strong linear correlation. For preschoolers, the PMV-PPD model as the thermal sensation evaluation criterion has a considerable bias, and the measured PMV-PPD model is not suitable for preschoolers.

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