Publisher's version can be found at https://doi.org/10.1016/j.buildenv.2021.107808

Study on the influence of air velocity on human thermal comfort under non-uniform thermal environment

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Highlights

• Combined effects of radiant temperature and air velocity on comfort were studied.

• High air velocity could improve thermal comfort in a non-uniform environment.

• High air velocity increased the deviation between thermal neutral and comfort.

• The air velocity was less sensitive with warmer thermal sensation.

Abstract

A differentiated thermal environment with different air temperature and radiant temperature can influence human thermal comfort levels when compared to the uniform thermal environment. The environment with the difference between indoor surface temperature and air temperature is the non-uniform thermal environment. However, existing research on the non-uniform thermal environment mainly focused on the impact of radiant environment on human thermal sensation, and few studies have focused on methods to improve the thermal comfort in the non-uniform thermal environment. In order to investigate the improvement of thermal comfort due to air velocity (va) in the non-uniform thermal environment, 20 subjects were recruited, and climate chamber was used in order to create air temperature and radiant temperature differential thermal environment (Δt = 0 °C, Δt = 5 °C, Δt = 10 °C, and va = 0 m/s, va = 0.6 m/s, va = 1.2 m/s). Furthermore, questionnaire survey combined with the physiological experiments was used, and the influence of va on thermal comfort in a hot environment was discussed. The results showed that increasing va can improve thermal comfort and reduce thermal discomfort caused by the difference between radiant temperature and air temperature. When va = 1.2 m/s, the percentage of thermal dissatisfaction can be reduced by a maximum of 20% (compared to when va = 0.6 m/s). Moreover, when va increased to 1.2 m/s, the limit value of acceptable operating temperature increased by 2 °C (compared to when va = 0.6 m/s). The results of this study will be useful in providing a theoretical basis for the design of the parameters of the indoor non-uniform thermal environment.

Keywords

Air velocity; Thermal comfort; Indoor air temperature; Radiant temperature; Non-uniform thermal environment

1. Introduction

With the constant development of low-energy green building systems, the radiant system has been widely used due to its high energy efficiency and providing good comfort [[1], [2], [3], [4]]. However, this has also led to the creation of differential thermal environment between indoor air temperature (ta) and surface temperature [5]. The environment with the difference (Δt) between surface temperature and air temperature is the non-uniform thermal environment, and the non-uniform thermal environment affected the heat dissipation ratio of the human body, which led to a change in the indoor human thermal comfort. Relevant research has been devoted to studying the effect of air velocity (va) on human thermal comfort improvement in a hot environment, but few studies have focused on va effect on human thermal comfort improvement in the non-uniform thermal environment.

The non-uniform thermal environment resulted in a change of heat dissipation ratio of the human body, among which the main influencing factor was the radiant temperature. Radiant temperature is an important parameter in the study of heat exchange between the human body and the environment, which can make the level of human thermal comfort different from the uniform thermal environment [6]. However, as the glass curtain wall and radiant end have been widely used in office and residential buildings, the average indoor radiant temperature is changing, which has intensified the creation of the non-uniform indoor thermal environment. Rowe's research showed that the change in operating temperature, caused by the movement of the sun around the building, will affect the voting result of thermal comfort [7]. Guan studied the characteristics of human thermal comfort in a high radiant thermal environment, and the results showed that the radiant temperature had a great impact on human thermal comfort [8]. Experiments by Hodder and Parsons [9] showed that for every 200 W/m2 increase in simulated solar radiation, the volunteers' thermal sensation votes increased by a scale unit. Alfano [10] showed that when the air temperature around the human body was within the comfort zone and when the surface temperature is higher than the air temperature, the temperature perceived by the human body may be higher than the temperature of the surrounding air. ASHRAE 55–2017 [11] gave the range of the asymmetry degree of radiant temperature of ceilings, floors and walls for heating and cooling. Therefore, it can be seen that the radiant temperature can affect human thermal comfort level. However, many studies on the radiant environment have focused on the impact of the environment on human thermal sensation [[12], [13], [14], [15]], and only a few were focused on the methods to improve human thermal comfort levels under radiant environment.

There are many ways to improve human thermal comfort, among which a proper increase in va has been shown to be an effective way to improve human thermal comfort in hot environments [[16], [17], [18], [19]]. The change in air velocity mainly affected the convective heat transfer between the human body and the environment, thus changing the heat dissipation of the human body [20]. A corresponding increase in va in a hot environment can not only improve the level of human thermal comfort, but also reduce the operating hours and energy consumption of air conditioning systems [21,22]. Studies [23,24] have found that when air temperature is above 28 °C, va can make the human body still feel comfortable. If va is below 0.6 m/s, for every 0.1 m/s increase in va, the comfortable ambient temperature of human body would increase by 0.3 °C. ASHRAE Standard 55–2017 [11] pointed out that when the ambient temperature exceeds the upper limit of acceptable temperature, it can be compensated by increasing va. In the naturally conditioned space controlled by the occupant, when va reach 1.2 m/s, the acceptable operating temperature limit for the human body increases by 2.2 °C (compared with va of 0.3 m/s). However, in existing research, the influence of va on human thermal sensation was mostly investigated in the uniform environment. In a hot environment with different air temperature and radiant temperature, there are few studies focused on the influence of va on human subjective response and thermal comfort. ASHRAE Handbook [25] provided the relationship between the temperature increase above the thermal boundary, and the va to be compensated in an environment where the air temperature differs from the radiant temperature. However, the correlation was determined only on the basis of the same skin heat loss in the two working conditions, and the relationship between the temperature increase and va to be compensated was not determined from the thermal comfort perspective. It was not clear how the combination of air temperature, radiant temperature, and va could improve human thermal comfort in a hot environment.

The aim of this study is to improve the understanding of the influence of va on human physiological and subjective thermal response in the non-uniform thermal environment. In the study, a thermal environment with different air temperature and radiant temperature was created in the climate chamber, and the physiological experiment and questionnaire survey were conducted. The influence of va on human thermal comfort in a hot environment was discussed. The improvement of human thermal comfort due to changing va in the non-uniform thermal environment was analyzed. Indoor temperature ranges are defined to meet the requirements of human thermal comfort in the non-uniform environment at different va. The results of this study will be useful in providing a theoretical basis for designing the non-uniform indoor thermal environment.

2. Materials and methods

2.1. Subjects

To reduce the impact of age and gender differences on human thermal sensation, 20 subjects were recruited in this study and participated in all experimental conditions in turn, all of whom were graduate students aged between 20 and 25 years (10 males and 10 females). Subjects studied regularly, slept enough, ate normally, and did not eat within 40 min before participating in the experiment. To reduce the influence of the outdoor ambient temperature on the subjects' thermal sensation, the subjects sat quietly in the preparation room at 26 °C for 30 min, and then entered the laboratory to begin the experiment. To ensure that subjects can complete the questionnaire accurately, the questionnaire was explained to all subjects prior to the experiment. The subjects' information is presented in Table 1.

Table 1. Detailed information about the subjects.

Gender	Number	Age	Height (cm)	Weight (kg)
Female	10	23.4 ± 0.7	160 ± 5.3	50.9 ± 7.1
Male	10	23.6 ± 1.2	172.5 ± 5.6	65.5 ± 11.8

2.2. Objective measurements

Indoor thermal environment parameters were considered which included air temperature, va, relative humidity, surface temperature, and carbon dioxide concentration. The sensitivity and accuracy of all instruments were checked before the experiment. Information on instruments for measuring environmental parameters are presented in Table 2.

Table 2. Measuring instruments in the climate chamber experiment.

Parameter	Type	Range	Accuracy
Surface temperature	CENTER-309	−200-1370 °C	±0.3%rdg+1 °C
Air temperature	TR-72wf	0–55 °C	±0.5 °C
Air humidity		10–95% RH	±5% RH
Air velocity	WFWZY-1	0.05–30 m/s	±0.05 m/s
Black globe temperature	HQZY-1A	−20-80 °C	±0.3 °C
CO2 concentration	TES-1370	0–6000 ppm	±1 ppm
Skin temperature	iButton DS1923	−20 °C-+85 °C	±0.5 °C
SpO2 heart rate	PHILIPS-DB12	35–100%	±2%
		30-250 bpm	±3 bpm
Blood pressure	HEM-7124	0–299 mmHg	±3 mmHg

Based on the process of body temperature regulation, skin temperature, blood pressure, oxygen saturation, and heart rate were chosen as physiological parameters. Temperature receptors were widely distributed below the surface of human skin, so skin temperature was one of the important physiological parameters that reflects the heat exchange between the human body and the environment [26,27]. At the same time, as the ambient temperature increases, the blood flow in the skin increases, and the blood flow involved in microcirculation decreases, which resulted in hypoxia [28]. The high temperature environment caused excitation of the human sympathetic nerve [29], heart rate increase [30], blood vessel constriction and changes in blood pressure [31]. Changes in heart rate and blood pressure can also predict changes in human metabolism [32]. Therefore, heart rate, blood pressure, and oxygen saturation were important physiological parameters for evaluating human thermal comfort in hot environments. Skin temperature was measured with iButton DS1923, blood pressure was measured with an electronic sphygmomanometer, while blood oxygen saturation and heart rate were measured with pulse oximeter. Data on instruments for assessing the physiological parameters are presented in Table 2.

2.3. Subjective questionnaires

The subjective questionnaire included indoor temperature, va, and the overall thermal evaluation of the indoor environment. ASHRAE 55–2017 seven-point scale [11] was adopted for assessing the thermal sensation vote (TSV), air velocity sensation vote (ASV), air velocity preference vote (APV). Thermal comfort vote (TCV) was conducted with a six-point scale [33]. For the evaluation of the indoor thermal acceptance vote (TAV), the 4-point intermittent scale was used, and the scales are shown in Table 3. Thermal satisfaction percentage (TSP) is based on the thermal acceptance vote of the subjects. It represents the ratio of people satisfied with the thermal environment to the total number of people. Subjects with thermal acceptability of +0.01 and + 1 were satisfied with the thermal environment, while subjects with thermal acceptability of −0.01 or −1 were not satisfied with the thermal environment. The neutral rate is based on the thermal sensation vote of the subjects. It represents under the same experimental condition, the percentage of subjects who chose TSV = 0 for their thermal sensation voting in the total number. The thermal comfort ratio is based on the thermal comfort vote of the subjects. It represents under the same experimental condition, the percentage of subjects who chose TCV = 0 and 1 for their thermal comfort voting in the total number.

Table 3. Subjective evaluation scales used in the study.

Scale	TSV	Scale	ASV	Scale	APV	Scale	TCV	Scale	TAV
3	Hot	3	Very high	3	Much higher	0	Very comfortable	−1	Clearly unacceptable
2	Warm	2	High	2	Higher	1	Comfortable	−0.01	Just unacceptable
1	Slightly warm	1	Slightly high	1	Slightly higher	2	Uncomfortable but acceptable	+0.01	Just acceptable
0	Neutral	0	Neutral	0	No change	3	Uncomfortable and unacceptable	+1	Clearly acceptable
−1	Slightly cool	−1	Slightly low	−1	Slightly lower	4	Very uncomfortable		
−2	Cool	−2	Low	−2	Lower	5	Unacceptable		
−3	Cold	−3	Very low	−3	Much lower				

2.4. Experimental conditions and procedure

In a hot environment, va can compensate for the increase in ambient temperature and can improve human thermal comfort [34]. Under different conditions of the thermal environmental, the influence of va on human thermal comfort was different. When va is higher than 0.25 m/s, it affects the acceptance of the thermal environment. ASHRAE 55–2017 [11] pointed out that when a person can control indoor va, the maximum acceptable va is 1.2 m/s and in order to account for the cooling effect of air velocity, va less than 0.1 m/s is defined as still air. Therefore, in order to study the influence of va on human thermal comfort in a hot non-uniform environment, va variable was introduced based on the radiant temperature and air temperature. Under the working conditions of ta = 28 °C and ta = 30 °C, Δt = 0 °C, Δt = 5 °C, Δt = 10 °C, and va = 0.1 m/s, va = 0.6 m/s, va = 1.2 m/s were selected for experimental research, where Δt represents the difference between surface temperature and air temperature. A total of 18 working conditions were set in the experiment, and the indoor va was controlled by a fan. Specific experimental conditions are presented in Table 4.

Table 4. Parameters of the indoor experimental environment (Mean ± SD).

Δt (°C)	Design condition			Air temperature (°C)	Surface temperature(°C)	Relative humidity (%)	Air velocity (m/s)	CO_2 concentration (ppm)
	t_a (°C)	t_s (°C)	v_a (m/s)					
0	28.0	28.0	0.1	28.3 ± 0.5	28.2 ± 0.5	50.5 ± 1.9	0.01 ± 0.02	675 ± 70
	28.0	28.0	0.6	28.3 ± 0.5	28.2 ± 0.5	50.5 ± 1.9	0.67 ± 0.02	675 ± 50
	28.0	28.0	1.2	28.2 ± 0.4	28.3 ± 0.4	47.8 ± 1.5	1.27 ± 0.03	660 ± 70

Δ*t* (°C)	Design condition			Air temperature (°C)	Surface temperature(°C)	Relative humidity (%)	Air velocity (m/s)	CO_2 concentration (ppm)
	t_a (°C)	t_s (°C)	v_a (m/s)					
5	28.0	33.0	0.1	28.0 ± 0.3	33.0 ± 0.4	47.8 ± 1.5	0.07 ± 0.03	860 ± 80
	28.0	33.0	0.6	28.3 ± 0.3	33.3 ± 0.5	52.6 ± 1.6	0.61 ± 0.01	750 ± 40
	28.0	33.0	1.2	28.3 ± 0.5	33.3 ± 0.3	53.2 ± 1.8	1.24 ± 0.02	670 ± 50
10	28.0	38.0	0.1	28.3 ± 0.4	38.3 ± 0.5	52.6 ± 1.6	0.01 ± 0.01	850 ± 70
	28.0	38.0	0.6	28.0 ± 0.4	38.2 ± 0.3	50.6 ± 1.3	0.62 ± 0.01	720 ± 60
	28.0	38.0	1.2	28.0 ± 0.2	38.3 ± 0.5	48.6 ± 1.2	1.22 ± 0.01	695 ± 55
0	30.0	30.0	0.1	30.3 ± 0.5	30.3 ± 0.3	53.2 ± 1.8	0.04 ± 0.02	660 ± 40
	30.0	30.0	0.6	30.2 ± 0.3	30.2 ± 0.4	47.6 ± 1.0	0.62 ± 0.01	720 ± 50
	30.0	30.0	1.2	30.0 ± 0.4	30.3 ± 0.5	47.8 ± 1.2	1.25 ± 0.03	695 ± 65
5	30.0	35.0	0.1	30.0 ± 0.4	35.2 ± 0.3	50.6 ± 1.3	0.02 ± 0.01	720 ± 50
	30.0	35.0	0.6	30.0 ± 0.5	35.3 ± 0.3	47.6 ± 0.9	0.64 ± 0.02	720 ± 50
	30.0	35.0	1.2	30.2 ± 0.5	35.3 ± 0.2	48.1 ± 1.3	1.21 ± 0.07	695 ± 65
10	30.0	40.0	0.1	30.0 ± 0.6	40.3 ± 0.5	48.6 ± 1.2	0.02 ± 0.01	795 ± 65
	30.0	40.0	0.6	30.3 ± 0.4	40.2 ± 0.4	50.2 ± 0.7	0.65 ± 0.05	720 ± 50
	30.0	40.0	1.2	30.2 ± 0.6	40.3 ± 0.5	51.2 ± 1.5	1.23 ± 0.01	695 ± 65

The experiment was conducted in the climate chamber of the Solar Energy Building and Environment in the State Key Laboratory of Green Building in Western China from May to July 2017. 20 subjects joined in each experimental condition. According to the temperature of the thermal comfort zone recommended by ASHRAE 55–2017 [11], the indoor air temperature for preparation room was set at 26 °C. Subjects changed to uniform clothes in the preparation room and glued the body surface tester on the skin surface. The experimenter explained the experimental process and taught the instruments to the subjects. Subjects stayed in the preparation room for 30 min and then entered the climate chamber for the experiment, which included completing subjective questionnaires and physiological parameter tests. During the experiment, five tests were carried out. According to existing research, a 30-min exposure can eliminate the impact of different environments to which subjects were previously exposed before the experiment. Therefore, the subjects completed the test every 10 min for a total of three times within 30 min of the start of the experiment, which represented the phase of thermal adaptation. Then, during the relatively stable phase of the experiment, the subjects completed the test every 15 min for a total of two times. We used the data of the relatively stable phase of the experiment for analysis, i.e., the results of the fourth and fifth tests, and the specific experimental process is presented in Fig. 1.

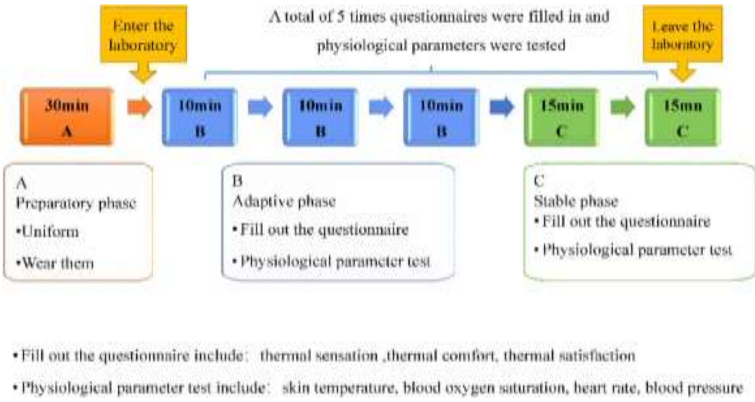


Fig. 1. Experimental procedure.

2.5. Data processing

To eliminate the influence of thermal resistance of clothing on human thermal sensation, the subjects wore uniform clothes, including underwear, long-sleeved shirts, trousers, and shoes. According to ASHRAE 55–2017 [11] and ASHRAE Handbook [25], the thermal resistance of clothing was assessed and calculated. The total thermal resistance of clothing of the subject was 0.72 clo, including 0.67 clo of the clothing and 0.05 clo of the seat heating resistance. The thermal resistance of clothing is obtained by equation (1).

$$I_{cl} = 0.835 \sum_{i=1}^{n} I_{clu,i} + 0.161 \quad (1)$$

where, Icl is a complete set of clothing thermal resistance (clo), and Iclu,i is the clothing thermal resistance of a single piece of clothing (clo).

Skin temperature was continuously measured during the experiment. Compared to the existing method of calculating average skin temperature, 10c method for measuring human skin temperature was adopted in this study. Due to its high reliability and good sensitivity [26], 10c method can accurately reflect the degree of change in skin temperature under hot and cold stimulation [35]. The 10c measurement points included forehead, left back, left chest, left hind limb, left forearm, abdomen, back of hand, front of right thigh, front of right calf, and right foot. Its calculation formula is shown in equation (2).

$$\begin{aligned} t_{msk} = {} & 0.06 \times t_{sk-forehead} + 0.12 \times t_{sk-back} + 0.12 \times t_{sk-chest} + 0.12 \times t_{sk-abdomen} + 0.08 \times t_{sk-arm} \\ & + 0.06 \times t_{sk-forearm} + 0.05 \times t_{sk-hand} + 0.19 \times t_{sk-thigh} + 0.13 \times t_{sk-calf} + 0.07 \times t_{sk-foot} \end{aligned} \quad (2)$$

where, tmsk is the average skin temperature obtained through the 10c method, and tsk-forehead is the average skin temperature of the forehead. Other abbreviations have similar meanings.

SPSS 20.0 was used to analyze test data of 20 subjects. The Shapiro-Wilk's test [36] was first used to determine whether the data were normally distributed, and then the F-test was used to investigate whether there were significant differences between the samples [37]. The significance level of all tests was set at 0.1, which means that the obtained results are statistically significant when $P < 0.1$.

3. Results

When the indoor temperature is high, human thermal comfort decreases, and va can effectively improve the human thermal comfort in the high temperature environment. Therefore, based on ta and radiant temperature, this paper defined three different va to study the influence of va on the subjective thermal response and human physiological parameters in the non-uniform thermal environment. The main results of the analysis are presented in the following subsections.

3.1. Changes in human physiological parameters at different air velocities

The variation of human blood pressure with va in different thermal environments is presented in Fig. 2. Under the same ta, systolic blood pressure (SBP) and diastolic blood pressure (DBP) showed a decreasing trend with increasing radiant temperature (tr), but the decreasing degree was not obvious. When ta was equal to tr, DBP and SBP showed an obvious downward trend with increasing va. Furthermore, the amplitude of the SBP variation with va was slightly larger than that of DBP. A two-sample t-test was used to analyze the difference in blood pressure under the influence of different va. It was noticed that SBP at ta = 28 °C and ta = 30 °C corresponding to different va were different (P < 0.1). When ta = 28 °C, there was a significant difference between DBP when va = 0.1 m/s and va = 1.2 m/s, and between DBP when va = 0.6 m/s and va = 1.2 m/s. There was no significant difference in DBP when ta = 30 °C. The specific analysis results are presented in Table 5.

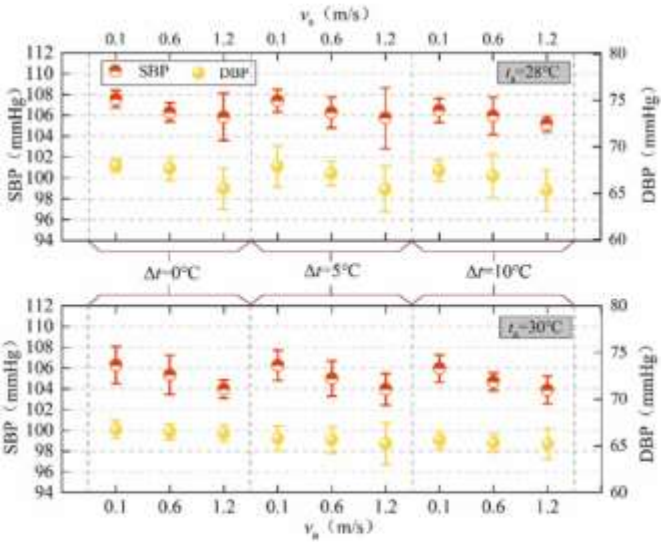


Fig. 2. Changes in blood pressure with different air velocities.

Table 5. P-values of physiological parameters between different air velocities.

Thermal environment		SBP (mmHg)	DBP (mmHg)	Heat rate (bpm)	SpO_2 (%)	t_{mst} (°C)
t_a = 28 °C	0.1 m/s and 0.6 m/s	0.05	0.14	0.08	0.001	0.02
	0.1 m/s and 1.2 m/s	0.02	0.0002	0.01	0.04	0.01
	0.6 m/s and 1.2 m/s	0.07	0.002	0.04	0.09	0.2
t_a = 30 °C	0.1 m/s and 0.6 m/s	0.01	0.64	0.08	0.02	0.05
	0.1 m/s and 1.2 m/s	0.002	0.42	0.04	0.0003	0.02
	0.6 m/s and 1.2 m/s	0.01	0.72	0.08	0.002	0.29

The average skin temperature in different thermal environments changes with changes in va, as shown in Fig. 3. At the same ta and surface temperature, the average skin temperature gradually decreased with increasing va, while the range of variations was small. When ta = 28 °C and Δt = 0 °C, the average skin temperature varies in a range of 0.43 °C, while the average skin temperature changes relatively little in other thermal environments when ta was 28 °C. When ta = 30 °C and Δt = 5 °C, the range of average skin temperature was 0.42 °C, and the range of skin temperature under other thermal environments was relatively small. A two-sample t-test was used to analyze the differences. Under two ta, there was a significant difference between the mean skin temperature at va = 0.1 m/s and va = 0.6 m/s, and between the mean skin temperature differences at va = 0.1 m/s and va = 1.2 m/s (P < 0.1). There was no significant difference in other heterogeneous thermal environments.

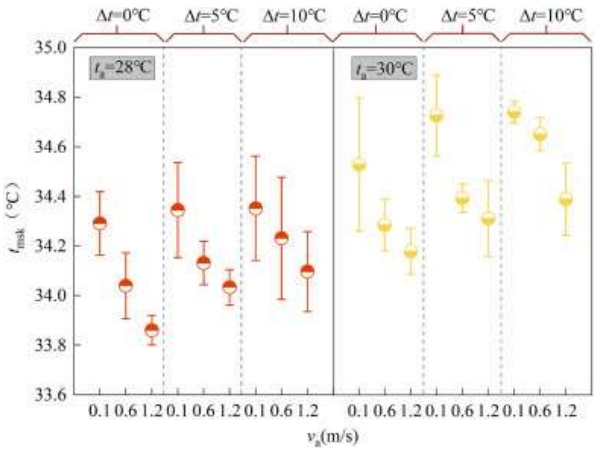


Fig. 3. Changes in the average temperature of human skin due to different air velocities.

The change in human heart rate with changing va is shown in Fig. 4. At the same va and tr, the heart rate gradually decreased with the increasing va. When ta = 28 °C and Δt = 0 °C, the heart rate changed by 4.9 bpm with the change in va, and the range of variations was small in other thermal environments when ta = 28 °C. When ta = 30 °C and Δt = 10 °C, the heart rate changed by 8.7 bpm with the change in va, and the range of variations was smaller in other thermal environments when ta = 30 °C. There were significant differences between heart rates at different va under two air temperatures.

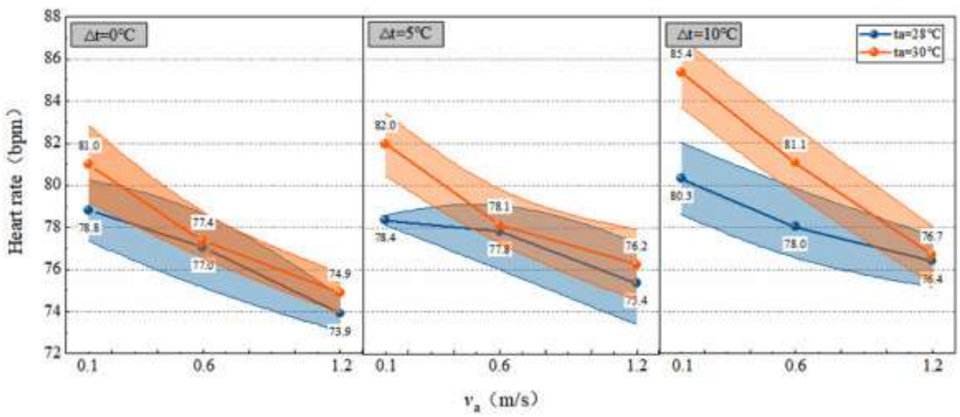


Fig. 4. Changes in the human heart rate with different air velocities.

The change in blood oxygen saturation (SpO2) with different va is shown in Fig. 5. It is obvious that SpO2 tends to decrease with increasing va in the same thermal environment. This may be due to the fact that as va increases, the air around the body became thinner and SpO2 tended to decrease. SpO2 showed a large difference between the two ta when Δt = 0 °C and va = 1.2 m/s. Under two ta, there was a significant difference between SpO2 corresponding to different va ($P < 0.1$), indicating that the change in indoor va had a significant impact on human SpO2.

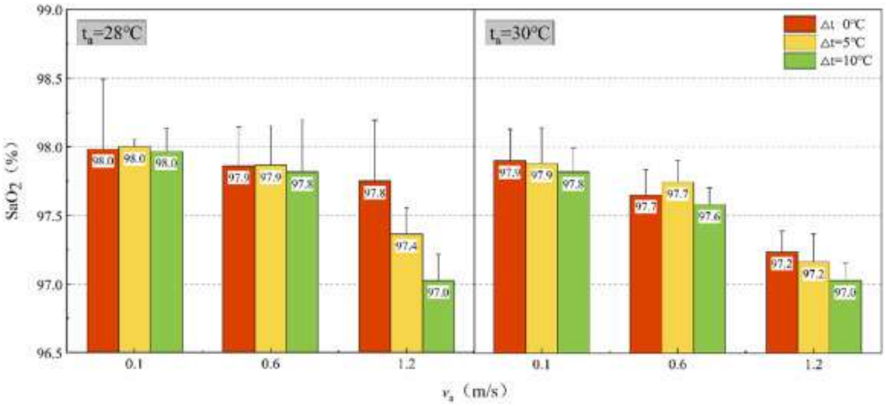


Fig. 5. Changes in SpO2 values with different air velocities.

3.2. Changes in subjective thermal responses at different air velocities

In Fig. 6, under different ta conditions, va showed different influences on human thermal response. The neutral rate is based on the thermal sensation vote of the subjects. It represents under the same experimental condition, the percentage of subjects who chose TSV = 0 for their thermal sensation voting in the total number. When ta was 28 °C, with an increase in va, the proportion of subjects with moderate thermal sensation(TSV = 0) gradually increased, the average thermal sensation value gradually decreased, and subjects got closer to the comfortable state. But as ta = 28 °C, Δt = 10 °C, and va = 0.6 m/s, the largest proportion of subjects had a moderate thermal sensation (75%), while when ta = 28 °C, Δt = 10 °C, and va = 1.2 m/s, the proportion of people with moderate thermal sensation was smaller. When ta = 30 °C, Δt = 5 °C, and va = 1.2 m/s, the largest proportion of people had moderate thermal sensation (55%). The proportion of moderate thermal sensations in other thermal environments was small, indicating that when ta is 30 °C, va from 0.1 m/s to 1.2 m/s cannot reduce the human thermal sensation to a moderate state. With high indoor temperature, the improvement degree of human thermal sensation due to va decreases. When the ta deviated from the comfort zone, the matching relationship among ta, tr, and va had a great influence on human thermal response.

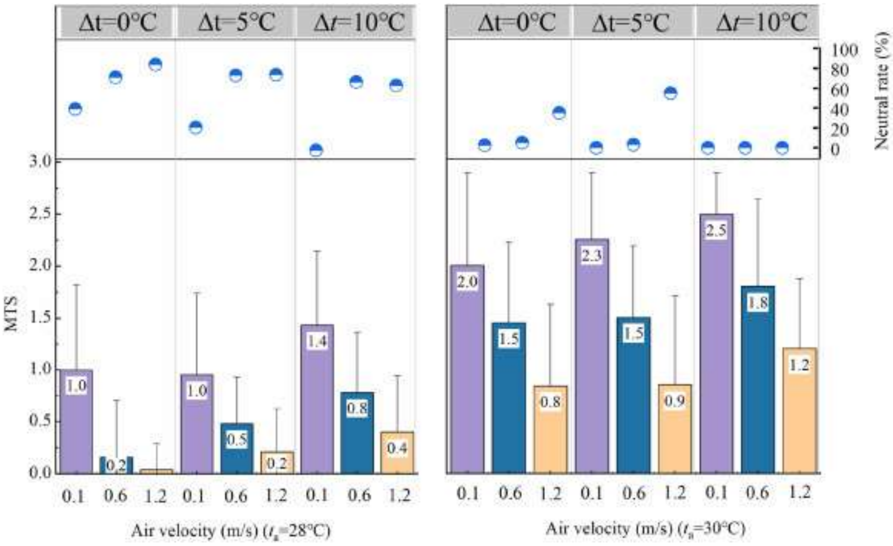


Fig. 6. Changes in the human thermal sensation with different air velocities.

The change in human thermal comfort due to va at two ta is shown in Fig. 7. When ta = 30 °C, Δt = 0 °C, and va = 1.2 m/s, 98% of the subjects feel comfortable. The TSV in this environment was 0.84 and it indicated that human mean thermal sensation was relatively hot. It also indicated that va increased the deviation between thermal neutral and comfort in the non-uniform thermal environment. The thermal comfort ratio is based on the thermal comfort vote of the subjects. It represents under the same experimental condition, the percentage of subjects who chose TCV = 0 and 1 for their thermal comfort voting in the total number. A comparison of human thermal comfort ratio under two ta showed that when ta = 28 °C and Δt = 0 °C, 5 °C, and 10 °C, human thermal comfort ratio increased by 54%, 42%, and 65% respectively with the change in va. When ta = 30 °C and Δt = 0 °C, 5 °C, and 10 °C, human thermal comfort ratio increased by 93%, 85%, and 75% respectively with the change in va. So when ta = 30 °C, Δt was less than 5 °C, the change in va had a larger influence on human thermal comfort. By comparing and analyzing the results when ta = 28 °C and ta = 30 °C, it can be noticed that when ta = 30 °C, va had a greater effect on human thermal comfort. At the same time, the thermal comfort ratio results are shown in Table 6.

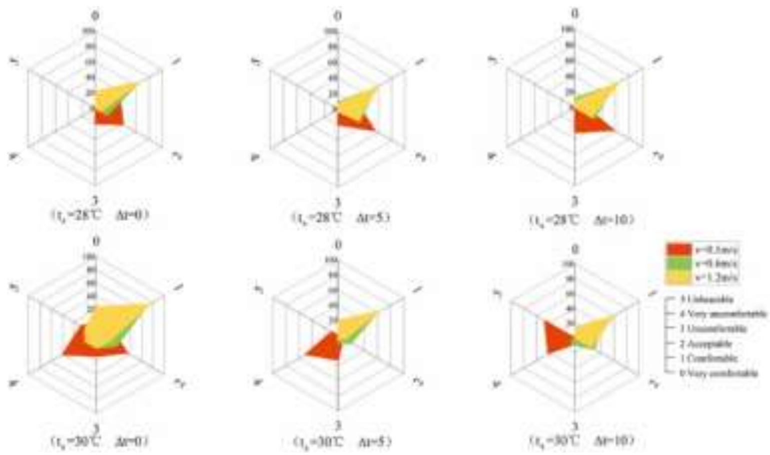


Fig. 7. Changes in human thermal comfort with different air velocities.

Table 6. Statistics of human thermal comfort at different air velocities.

t_a (°C)	Δt (°C)	v_a (m/s)	Comfortable proportion (%)	t_a (°C)	Δt (°C)	v_a (m/s)	Comfortable proportion (%)
28	0	0.1	38	30	0	0.1	5
		0.6	82			0.6	85
		1.2	92			1.2	98
	5	0.1	25		5	0.1	0
		0.6	65			0.6	70
		1.2	67			1.2	85
	10	0.1	10		10	0.1	0
		0.6	71			0.6	53
		1.2	75			1.2	75

Changes in the thermal satisfaction percentage with different va are shown in Fig. 8. The combination with the highest thermal satisfaction percentage was when ta = 28 °C, Δt = 0 °C, and va = 1.2 m/s. In addition, it was not difficult to notice that at the same ta and tr, and with increasing va, the satisfaction of subjects with thermal environment increased. When ta = 28 °C and Δt = 10 °C, the satisfaction of subjects varied with the va and increased to a large extent. When Δt = 0 °C, the range of variations was small. However, when ta = 30 °C, the degree of satisfaction has changed greatly under different tr. This phenomenon suggested that the increase in va made the human body more receptive to a warm indoor thermal environment. Under the same ta and va, the degree of satisfaction decreased with increasing tr. In addition, it can be seen that with increasing Δt, the thermal satisfaction percentage decreased at different va.

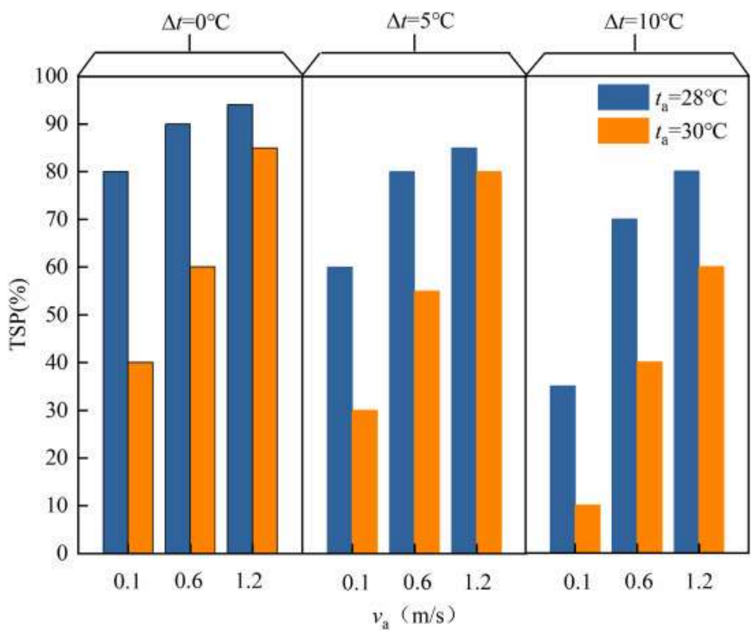


Fig. 8. Changes in the thermal satisfaction percentage (TSP) with different air velocities.

The relationship between mean skin temperature (tmsk) and TSV at different va is shown in Fig. 9. When va is 0.6 m/s, the relationship between TSV and tmsk is shown in equation (3) (R2 = 0.85):

$$TSV = -94.10 + 2.77 \times t_{msk} \quad (3)$$

When va is 1.2 m/s, the relationship between TSV and tmsk is shown in equation (4) (R2 = 0.92)

$$TSV = -75.11 + 2.22 \times t_{msk} \quad (4)$$

when va = 0.6 m/s, the average skin temperature corresponding to the human thermal neutrality was tmsk = 34.0 °C. When va = 1.2 m/s, the average skin temperature corresponding to the human thermal neutrality was tmsk = 33.9 °C, the reason for this may be that the increase of air velocity intensified the human convective heat transfer [38], which made the skin temperature decreased when the human is in a thermal neutral state.

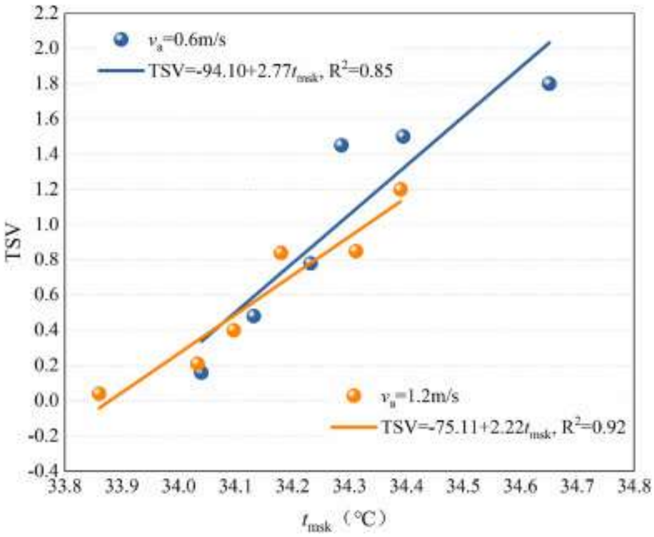


Fig. 9. Relationship between mean skin temperature (tmsk) and thermal sensation vote (TSV) at different air velocities.

Relevant studies showed that head's cooling could effectively reduce human thermal sensation [39], in this experiment only the head was exposed to air, with the increase of air velocity, the temperature of subjects' head decreased, which led to the decrease of thermal sensation. However, in the process of calculating the average skin temperature, the weight coefficient of forehead temperature is only 0.06, and the average skin temperature was covered by the temperature of other non-exposed areas. As a result, the average skin temperature was still high when va = 1.2 m/s. This may be the reason for the inconsistency between Eq. (3) and Eq. (4).

3.3. Influence of air velocity on thermal dissatisfaction in hot environments

Air velocity can improve human thermal comfort in a hot environment. Therefore, thermal dissatisfaction percentage (TDP_V) at different va and thermal dissatisfaction percentage (TDP) corresponding to va of 0.1 m/s are adjusted by the fitting method commonly used in thermal comfort studies. When va is 0.6 m/s, the thermal dissatisfaction model of human body is as follows:

$$TDP_{V=0.6m/s} = \exp(1.58 + 0.04 * TDP_{V=0.1m/s} + (-1.52 * 10^{-4}) * TDP_{V=0.1m/s}) \quad (5)$$

When va is 1.2 m/s, the thermal dissatisfaction model of human body is as follows:

$$TDP_{V=1.2m/s} = \exp(1.92 + 0.01 * TDP_{V=0.1m/s} + 1.55 * 10^{-4} * TDP_{V=0.1m/s}) \quad (6)$$

Equations (5), (6) can clearly express that in a hot environment, an increase in va can reduce the human thermal dissatisfaction percentage.

Human TDP with va = 0.1 m/s and TDP_V with va = 0.6 m/s and 1.2 m/s were plotted. In a hot environment, TDP was reduced by 10%–30% when va was 0.6 m/s compared with va= 0.1 m/s. When va was 1.2 m/s, TDP decreased maximum 20% compared with va = 0.6 m/s. It can be seen that the thermal satisfaction can be effectively improved and human discomfort can be reduced by increasing va in hot environments (see Fig. 10).

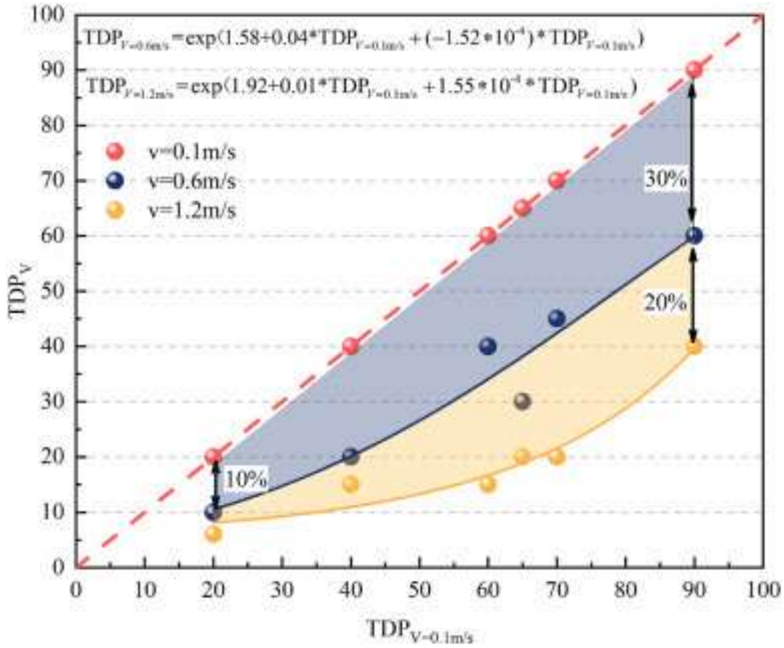


Fig. 10. Thermal dissatisfaction model at different air velocities.

3.4. Changes in sensation and preference of air velocities in hot environments

This experiment compared the subjects' sensation and preference of indoor air velocities under different experimental conditions. By comparing and analyzing the results when ta = 28 °C and ta = 30 °C, it can be noticed that with the increase of air temperature, the subjects' sensation of air velocity gradually weakened, and the percentage of subjects wishing to increase air velocity increased gradually. When ta = 28 °C, va = 0.1 m/s, the subject's air velocity sensation decreased by 0.1 with the change in Δt. When ta = 30 °C, va = 0.1 m/s, the subject's air velocity sensation decreased by 0.7 with the change in Δt. It can be noticed that the higher ambient temperature aggravated the decrease of air velocity sensation of subjects. When ta = 28 °C, va = 1.2 m/s, the percentage of subjects wishing to increase air velocity was 0. When ta = 30 °C, va = 1.2 m/s, the subject still had relatively high expectations of increasing air velocity, which indicated that when va = 1.2 m/s, ta = 28 °C, the air velocity is slightly higher.

When va = 0.1 m/s, with the increase of ambient temperature, subjects' MTS increased from 1.0 to 2.5, air velocity sensation reduced from −1.2 to −2.6, the percentage of subjects wishing to increase air velocity increased from 73.3% to 100%. When va = 0.6 m/s, with the increase of ambient temperature, subjects' MTS increased from 0.2 to 1.8, air velocity sensation reduced from −0.1 to −1.0, the percentage of subjects wishing to increase air velocity increased from 26.7% to 73.3%. When va = 1.2 m/s, with the increase of ambient temperature, subjects' MTS increased from 0 to

1.2, air velocity sensation reduced from 0.4 to 0.1, the percentage of subjects wishing to increase air velocity increased from 0% to 31.6%. So under warmer thermal sensation, human air velocity sensation decreased and the percentage of subjects wishing to increase air velocity improved (see Fig. 11).

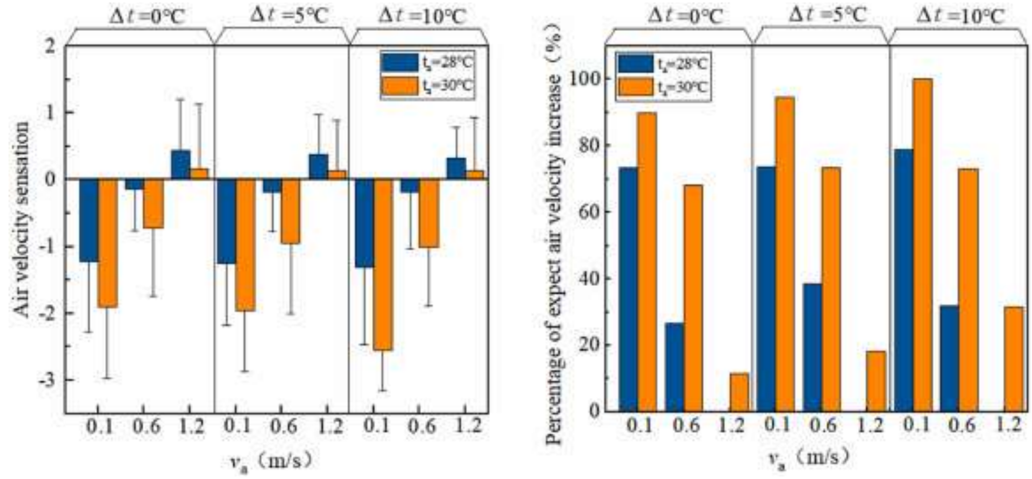
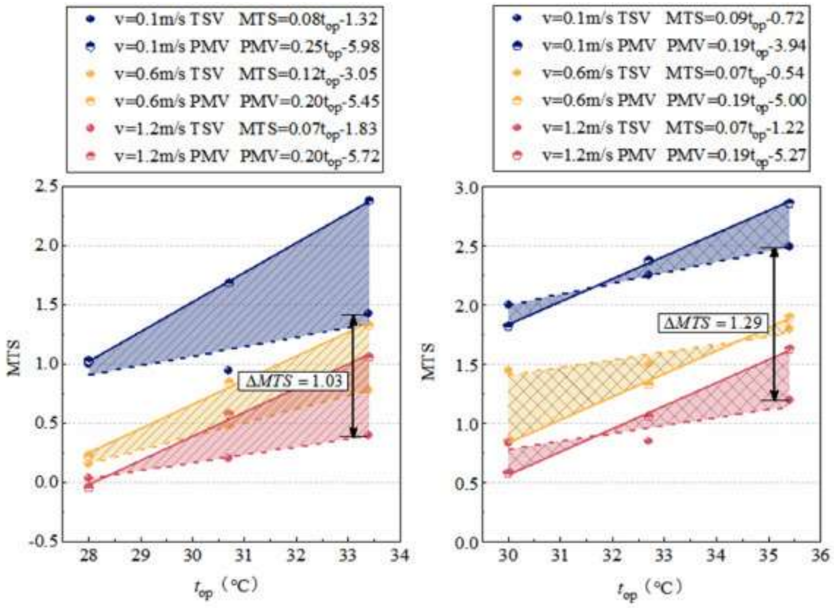


Fig. 11. Changes in the human sensation and preference of indoor air velocities under different experimental conditions.

4. Discussion

4.1. Comparison of MTS and PMV results at different air velocities

A comparison between TSV and PMV corresponding to different va in hot environments is shown in Fig. 12. When ta = 30 °C, the improvement in actual thermal sensation was greater with the increase in va in the same thermal environment than for the situation when ta = 28 °C. When ta = 28 °C and Δt≠0 °C, there was a significant difference between TSV and PMV. When ta = 28 °C, the difference between MTS and PMV gradually decreased with increasing va at the same tr. When ta = 30 °C, the difference between PMV and TSV was smaller than at ta = 28 °C under the same thermal environment, and the difference between PMV and TSV tended to increase with increasing va. This is because the PMV model is based on the equation of thermal balance of the human body in a comfortable state. In the uncomfortable state of hot environment, the correlation coefficients are not modified. When ta = 28 °C, with increasing va, the subjects gradually reached a comfortable state, so the difference between PMV and TSV gradually decreased. The PMV model considered only the effect of va on the convective heat transfer coefficient and did not consider the influence of va on the rate of evaporation of human sweat in a hot environment. Increasing va increased the body sweat evaporation heat transfer coefficient, so the PMV model underestimated the ability of va to improve the thermal sensation in a hot environment and when ta = 30 °C, the difference between PMV and TSV tended to increase. At the same time, Fig.12also showed that as the indoor ta increased, the improvement in thermal sensation due to va was gradually enhanced.



(a) *t*a=28℃ (b) *t*a=30℃

Fig. 12. Comparison between TSV and PMV under different air velocities.

4.2. Comparison with existing research results

Existing research has shown that increase in va within a certain range can compensate for the increase in temperature. The comparison of results from this study with the existing research is presented in Table 7. In this experiment, when va = 1.2 m/s and operating temperature was 30 °C, 32.7 °C and 35.4 °C, the MTS of subjects was similar to the MTS when operating temperature was 28 °C, 30.7 °C and 33.4 °C and air velocity was 0.1 m/s. This is in line with the existing research results, i.e., when va reached 0.8–1 m/s, the thermal sensation deviated about 2–3 °C. In this study, when operating temperature was 28 °C and 30 °C, and va was 1.2 m/s, the largest number of subjects acknowledged that the current environment is moderate and comfortable. Compared to the research results of Luo [44], under working conditions of 28 °C or 30 °C, va of 0.4–0.6 m/s or 0.7–0.9 m/s could meet the human thermal comfort requirements, respectively. However, the clothing thermal resistance of subjects was different in the two experiments. In Luo's experiment, the uniform clothing thermal resistance of the subject was 0.57 clo, while in this experiment, the uniform clothing thermal resistance of the subject was 0.72 clo, so to achieve the same thermal sensation, the required va was higher in this experiment. Huang [45] showed that in conditions of 28 °C and 30 °C, a minimum va of 0 m/s and 1 m/s can provide a thermal sensation below 0.5. Compared with the results of this experiment, when the operating temperature was 28 °C and va was 0.1 m/s, the MTS of the subjects was 1. When the operating temperature was 30 °C and va was 1.2 m/s, MTS of the subjects was 0.84. The mean thermal sensation of the subjects was higher under the same condition in this experiment, which was due to the fact that the fan was relatively far from the subjects in the experiment. Therefore, the influence of air outlet distance should also be considered in studying the influence of va on human thermal comfort.

Table 7. Comparison with other studies on the influence of air velocity on thermal comfort.

Author	Air velocity (m/s)	Temperature range (°C)	Relative humidity (%)	Clothing thermal resistance (clo)	Activity	Relevant conclusion
Konz [40]	0.4 0.8 1.2	25.6 27.8 30	50%	0.6	Seated	When the air velocity increased by 0.1 m/s, human thermal comfortable temperature increased by 0.27 °C.
Rohles [41]	0–1	22.2–29.6	–	0.6	Seated	When the air velocity was 0.8 m/s, the upper limit of human comfortable temperature range increased from 26 °C to 29.5 °C.
McIntyre [42]	0–2	22–30	–	0.38–0.48	Seated	When the air velocity was 0.8 m/s, the upper limit of human acceptable temperature range was 28 °C.
Arens [17]	1.4	25–30	50%	0.5	Seated	When the air velocity was 1.4 m/s, human comfortable temperature was 31 °C.
Fang [43]	1.0	26 28	60%–70%	0.5	Seated	When the air velocity reached 1 m/s, human thermal sensation shifted about 2 °C.
Luo [44]	0.4–0.6 0.7–0.9	26 28 30	45%–55%	0.57	Seated	When air temperature was 28 °C and 30 °C, the air velocity was 0.4–0.6 m/s and 0.7–0.9 m/s respectively, and the thermal comfort requirements were met.
Huang [45]	0.6 1.0 1.5 2.0	28 30 32 34	40%–50%	0.57	Seated	When air temperature was 28 °C and 30 °C, the minimum air velocity was 0 m/s and 1 m/s, and human thermal sensation was below 0.5.
Wang [46]	0.1 0.6 1.0	26 29	–	0.4	Seated	When the air velocity reached 1 m/s, human thermal sensation shifted about 3 °C.
Tian [47]	1.0–1.2	28 30 32	70% 80% 90%	0.46	Seated	When air temperature was from 28 °C to 32 °C, air velocity was from 1.0 to 1.2 m/s, and human felt comfortable.
Ji [48]	0.25 0.34 0.42 0.70 0.95 1.36	27.1 28.1 29.1 30.1	68.8%–70.3%	0.5	Seated	When the air velocity was 0.8 m/s, temperature and relative humidity were 29.3 °C and 70% respectively, and human felt comfortable.
Present study	0 0.6 1.2	28 30	–	0.72	Seated	When the air velocity reached 1 m/s, human thermal sensation shifted about 2 °C.

4.3. Comparison with existing standards

Description point analysis was performed on the graph of acceptable operating temperature range and va in ASHRAE 55–2017 in Fig. 13, which is suitable for subjects with the clothing thermal resistance of 0.5 clo and 1.0 clo and with the metabolic rate between 1.0 and 2.0met. In this experiment, subjects were sitting with a metabolic rate of 1.0 met, but subjects wore uniform clothing with the thermal resistance of 0.72 clo, which is different from ASHRAE 55–2017. The humidity ratios of the environment were both 0.01. Simultaneously, the range of acceptable temperature were both obtained at va = 0.6 m/s and 1.2 m/s. In ASHRAE 55–2017, when the clothing thermal resistance of subject was 0.5clo, va was 0.6 m/s, the range of acceptable temperatures was from 26.4 °C to 29.8 °C, while when va was 1.2 m/s, the range of acceptable temperatures was from 27.5 °C to 30.9 °C. In this experiment, when va was 0.6 m/s, the range of acceptable temperatures was from 25.5 °C to 27.3 °C, and when va was 1.2 m/s, the range of acceptable temperatures was from 26.8 °C to 29.3 °C. In this experiment, the acceptable temperature range under different va was lower than in the ASHRAE Standard 55–2017 due to several reasons: i) In this experiment, the clothing thermal resistance was 0.72 clo, while the acceptable temperature range in the ASHRAE Standard 55–2017 was obtained with a clothing thermal resistance of 0.5 clo; and ii) The non-uniform thermal environment exacerbates the degree of discomfort felt by human body, and made the subjects' acceptable temperature range, under the hot non-uniform thermal environment, lower than that in the uniform thermal environment of ASHRAE Standard 55–2017. At the same time, comparing the acceptable temperatures of the subjects under two va in this experiment, it was found that the limit value of human acceptable temperature can be effectively increased by appropriate increase in va in hot environments, which is in line with the va compensation function in ASHRAE Standard 55–2017. At the same time, when va was 1.2 m/s, the acceptable temperature range increased by 2 °C compared to va of 0.6 m/s. Compared with the ASHRAE Standard 55–2017, va increased from 0.6 m/s to 1.2 m/s, and the acceptable temperature limit increased by 1 °C, indicating that va in the non-uniform thermal environment had a significant effect on improving the thermal comfort of the human body. When the percentage of thermal satisfaction of subjects was 90%, it was noticed that MTS was 0.28 when va was 0.6 m/s, while MTS was 0.30 when va was 1.2 m/s, and both were lower than the limit value of MTS = 0.5. This suggests that it might be inappropriate to use human thermal sensation as the only evaluation index in the non-uniform thermal environment with high air velocity (see Fig. 14).

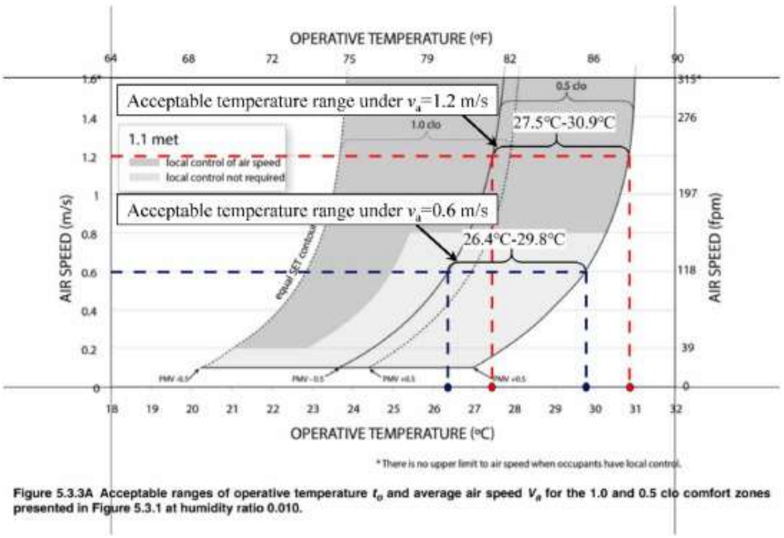


Fig. 13. Acceptable temperature ranges at different air velocities in ASHRAE Standard 55–2017 [11].

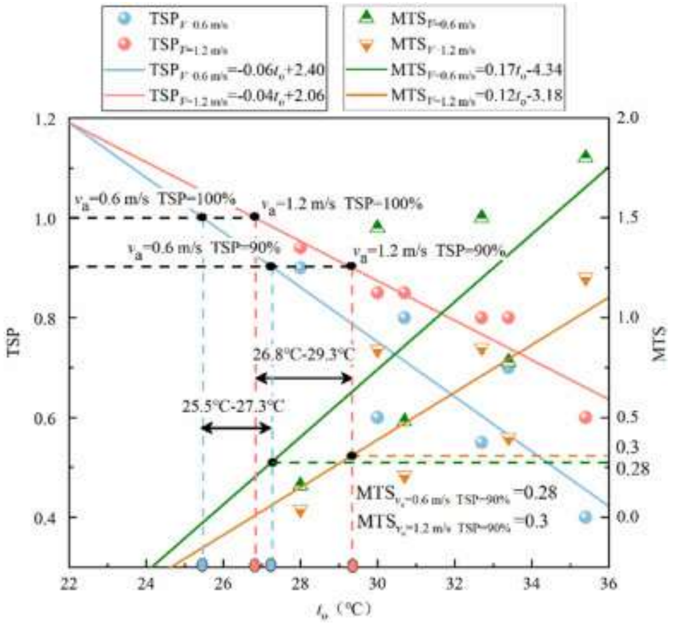


Fig. 14. Acceptable temperature ranges and MTS at different air velocities.

5. Conclusions

By comparing the subjective reactions and changes in physiological parameters of subjects under different combinations of ta, tr, and va, this study found that increasing va can improve the human thermal comfort and reduce thermal discomfort caused by the difference between tr and ta in hot environments. The specific conclusions are as follows:

1) Under the influence of va, human thermal neutrality and thermal comfort appear to be separated in the non-uniform thermal environment. By increasing indoor ta, the improvement of thermal sensation due to va is gradually enhanced.
2) In a hot environment, increasing va can improve the human thermal comfort and reduce the thermal discomfort caused by the difference between tr and ta. When va = 0.6 m/s, the dissatisfaction with thermal environment can be reduced by 10%–30% when compared to the situation of va = 0.1 m/s. When va is 1.2 m/s, the dissatisfaction can be reduced by a maximum of 20% when compared to va = 0.6 m/s.
3) In a hot environment, the limit value of acceptable temperature increases with the increase in va. When va was 0.6 m/s, the acceptable operating temperature of the subjects ranged from 25.5 °C to 27.3 °C. When va was 1.2 m/s, the acceptable operating temperature of the subjects ranged from 27.5 °C to 30.9 °C.
4) In a hot environment where ta and ta were not equal, the influence of ta and tr on human thermal comfort should be analyzed together. Based on the operating temperature, the evaluation should be performed from the perspectives of ta, tr, and va.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was supported by the State Key Program of National Natural Science Foundation of China (No. U20A20311), the National Natural Science Foundation of China (No. 51878532), the National Natural Science Foundation of China (No. 52078408), and the National Natural Science Foundation of China (No. 52008329).

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