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Analysis of Regulation Characteristics in Acceptable Thermal Comfort Zone under Cooling Conditions

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Abstract. Residents mainly set the temperature at the range of 25℃ to 27℃ under cooling conditions. However, they may feel uncomfortable after staying a period in a steady-temperature environment. To make themselves more comfortable, residents will change their postures and even regulate the temperature. To analyze the regulation characteristics, this study combined thermal environment testing, questionnaire survey, video collection, and data mining methods to collect the thermal environment and comfort background, posture, and temperature regulation characteristics. The results showed that Mean Thermal Sensation Vote gradually deviated from neutrality and tended to be cooler even though the thermal environment and thermal comfort were both within the acceptable zone. 12 typical posture regulations were captured and divided into 3 categories: head (face) postures, trunk postures, and limb postures. Head (face) postures were the concentrated expression of adaptive postures (80%). Although the total posture frequency remained unchanged, the head (face) postures gradually increased, which reflected the increase in discomfort. The temperature regulations accounted for nearly 25%. Most people (90%) regulated the temperature at 1°C with the frequencies of once or twice, and they preferred to set the temperature up than down. In the first 3 hours, there would be a regulation peak every 20 or 30 minutes, while the regulation decrease after 3 hours.

1 Introduction

The acceptable thermal comfort zone temperature for personnel is within 24℃ to 28℃[1]. Previous studies have shown that residents mainly regulated the temperature at 25℃ to 27 ℃ under cooling conditions [1-4]. When users stay in an air-conditioning thermal environment, conscious and unconscious regulation behaviors are often used to improve the thermal discomfort caused by the steady-state thermal environment, including regulating the setting environmental parameters and personal posture regulation, etc.[5-8]. When humans stay indoors, there is feedback between thermal comfort and adaptive behaviors[9]. If the human body feels uncomfortable, each part of the body will produce a certain reaction. When the occupants cannot improve their thermal comfort only through posture regulations, they may regulate the set temperature to change the environmental parameters to meet their thermal comfort requirements. However, there is a lack of linking posture regulations with thermal comfort requirements under an acceptable thermal environment. Besides, figuring out the behaviors of temperature regulation remains a question.

To analyze the regulation characteristics in acceptable thermal comfort zone under cooling conditions, this study combined thermal environment testing, questionnaire survey, and video collection methods to collect the thermal environment, thermal comfort, and posture characteristics at the temperature from 25℃ to 27℃. According to the monitoring data of the big data platform, the set temperature regulation behaviors characteristics from 25 ℃ to 27 ℃ were defined.

2 Methodology

The size of the laboratory chamber was 7.0 m in length, 4.0 m in width, and 2.4 m in height. We selected a certain brand of the vertical cabinet air conditioner as the experimental equipment. The average temperature and the relative humidity of the laboratory outdoor were controlled to 35.5 ℃, 59%, respectively [1]. The laboratory

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layout is shown in Fig. 1. According to the distance from the air outlet of the air conditioner, 6 test positions were set in the center of the room. The distances from position 1 to position 6 were respectively 2.0 m, 2.5 m, 3.0 m, 4.0 m 5.0 m, and 6.0 m.

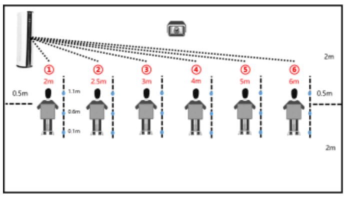

Fig. 1. Laboratory layout and measuring point layout.

There were 6 sets of test conditions. The set temperatures were 25 °C, 26 °C, and 27 °C, respectively. The wind speeds were set to low to high wind, and the wind direction was set to sweep air. Each set of conditions runs for 30 minutes.

Thermal environment testing parameters included air dry bulb temperature, relative humidity, air velocity, and black bulb temperature. There were 54 volunteers in the experiment. They were all dressed in typical summer clothes (the thermal resistance of the clothing was 0.5 clo). The content of the questionnaire included personal information and the thermal sensation of the volunteers. During the whole experiment, the volunteers remained sedentary (metabolic rate was 1.0 met), and the volunteers filled out a questionnaire every 5 minutes. The video recorder was arranged in front of the volunteers. The whole experiment behaviors of the 54 volunteers were recorded completely, with a total of 2160 minutes of video.

Based on the big data monitoring platform of a certain brand of household air conditioners, Python tools was used to select randomly the operation data of 500 room air conditioners of the same brand in Chongqing from June to August 2016 so that the temperature regulation behaviors within the set temperature of 25 °C to 27 °C were analyzed.

3 Results

3.1 Thermal environment and thermal comfort backround

It can be seen from Fig. 2 that the average temperature of each location was in the acceptable temperature range (from 24.0 °C to 28.0 °C). The average wind speeds of most positions were all within the acceptable wind speed range (below 0.3 m/s). The average relative humidity of each location was in the acceptable humidity range (from 40% to 70%), and the average radiation temperature at each location was 31.1 °C.

We substituted the relevant indicators into the PMV calculation formula to obtain the PMV value at each position. It was found from Fig. 3 that about 90% of the overall PMV and TSV values were within (-1.0, 1.0), which both were close to the thermoneutral state. According to the PMV-PPD model, the thermal environment was basically in the 80% acceptable thermal comfort interval.

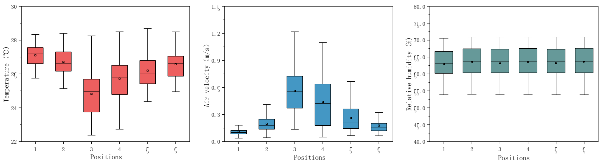

Fig. 2. Various indicators of thermal environment.

The time trend diagram of MTSV was made with a step of 5 minutes, as shown in Fig. 4. It can be observed that the hourly MTSV values deviated to different degrees and tended to be cooler with time increasing. It indicated that volunteers would feel cooler and more uncomfortable after staying in a steady-state environment for a period.

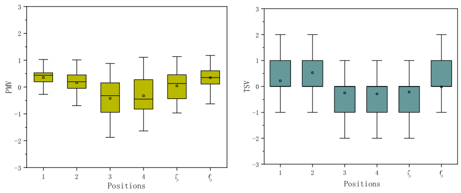

Fig. 3. PMV and TSV value distribution.

3.2 Posture regulations characteristics

A total of 4311 posture occurrences were extracted. According to the 3 main parts of the human body(head (face), trunk and limbs), 12 typical postures were divided into 3 categories, as shown in Table 1 and Fig. 6.

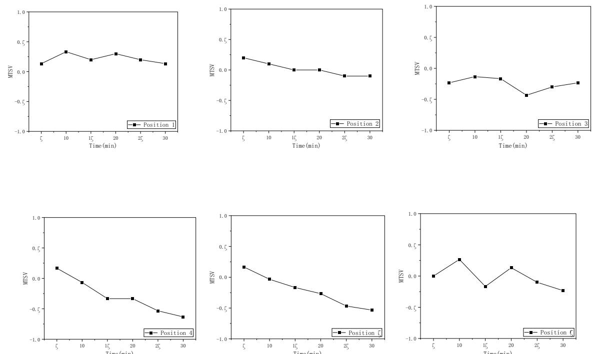

Fig. 4. MTSV time trend diagram.

It can be seen from Table 2 that the posture frequency of each part was ranked as follows: head (face) posture frequency was the most (78.5%), followed by limb posture (13.7%), and trunk posture frequency was the smallest (7.8%). The head (face) postures were the concentrated expression of human adaptive action.

In the first 5 minutes, after the person had just experienced the thermal experience from hot to cold, the human body produced more postures to adapt to environmental changes (As shown in Fig. 5). After 5 minutes, the human body had relatively adapted to the indoor environment, and the total posture frequencies

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were partially reduced but remained stable with time. In total postures, the head (face) postures gradually increased, and the trunk and limb postures decreased slightly.

Table 1. Posture Categories.

categories	Typical posture
Head (face) posture	Yawning, drinking water, rubbing the face (scratching/ grabbing the head/ eyes/ nose/ face/ ears), sneeze/ cough/ wipe nose, drape/ tie hair
Trunk posture	Rubbing other parts of the body (back/ shoulders/ waist), dressing (dressing/ pulling clothes/ pulling cuffs/ tightening clothes), undress (undress/ roll-up sleeves)
Limb posture	Rubbing legs, rubbing the hands (arms/ palms), placing hands on legs (under/ between legs), cover legs with clothes

Table 2. Frequency of various types of postures.

Posture categories	Total frequency		Per volunteer frequency in a single condition	
Head (face)	3383	78.5%	15.07	78.2%
Trunk	338	7.8%	1.55	8.0%
Limb	590	13.7%	2.66	13.8%

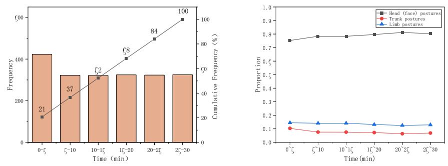
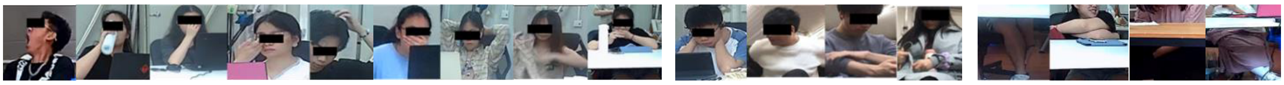
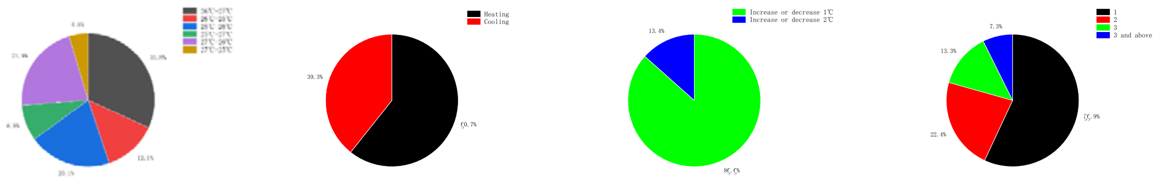


Fig. 5. Total and each part of regulation behaviors frequencies changed in each 5 minutes.



a) Head (face) postures. b) Trunk postures. c) Limb postures.

Fig. 6. Postures video clips.



a) b) c) d)

Fig. 7. a) Each temperature regulation behavior. b) Heating or cooling behaviors. c) Heating or cooling 1 or 2°C behaviors. d) Regulation times. e) Regulation time histogram.

3.3 Temperature regulations characteristics

1) Total frequency. The total number of effective regulations was 3928 times, of which the regulation ratio from 25 °C to 27 °C was 23.8%. It was observed from Fig. 7a) that nearly 80% of the regulation were heating or cooling around 26 °C.

2) Heating or cooling trend. It was given from Fig. 7b) that 60% of the regulation were heating approximately, while 40% were cooling, which indicates that residents tended to turn on the set temperature within 25 °C to 27 °C.

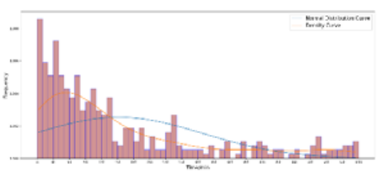


Fig. 8. Regulation time histogram

3) Amplitude. As shown in Fig. 7c), 90% of the heating or cooling behaviors were 1 °C, which is a great demand of residents' temperature regulation.

4) Times. From Fig. 7d), it was described that the proportion of regulating the temperature once was the highest (56.9%), followed by the twice (22.4%), which means that the residents mainly regulated the set temperature 1 or 2 times in an acceptable thermal environment.

5) Temperature regulation time. In the first 10 minutes, residents may set or regulate the initial temperature by turning on the machine to improve the original ambient temperature of the room and achieve the initial thermal comfort state (As shown in Fig. 8). In the first 3 hours, there would be a regulation peak every 20 to 30 minutes, which indicated that the residents felt uncomfortable in the current environment every 20 to 30 minutes. When the single operation time exceeds 3 hours, the regulation behaviors were less.

4 Discussion

Under the mainly set temperature from 25 °C to 27 °C, the indoor thermal environment was in the acceptable zone no matter how users regulated the set temperature. Although 90% of the overall PMV and TSV values were corresponding to the acceptable environment, the users' MTSV values gradually deviated from thermal neutrality and tended to be cooler. It was indicated that after staying a period in the acceptable thermal environment, users may be unsatisfied with the steady-state environment. Furthermore, it was also implied that users may just need slight temperature fluctuations to meet their needs for dynamic thermal comfort.

When humans felt uncomfortable in the air-conditioning environment, they would have certain behaviors which were composed of unconsciously posture regulation and consciously set parameters regulations. Each part of the body would be directly reacted to the discomfort, which is called posture regulation. Due to the head and face being the most sensitive parts of the human body to the thermal environment changes, users would mainly regulate these postures (80%) to express their feelings and adapt to the thermal environment. The increase in the frequency of head (face) posture over time represented the increase in human discomfort.

If the level of discomfort was tolerable, users could adapt to it only by increasing the posture regulations. Nevertheless, when users cannot tolerate the uncomfort or the increase in the posture regulations was insufficient, users would be more likely to regulate the set temperature. In terms of the proportion of the temperature regulations within 25 °C to 27 °C, it proved that the need for the slight temperature fluctuations cannot be ignored. Based on the result of temperature regulation time, it was inferred that 20 to 30 minutes was the tolerable upper limit time or the comfort time under the acceptable environment. Most people (90%) regulated the temperature in the range of 1°C with the frequencies of once or twice and set the temperature up rather than down, which was the users' preference of temperature regulation.

Air-conditioning manufacturers can design the created air conditioners to automatically recognize residents' posture regulations based on image recognition technology. When the frequency of posture regulation behaviors occurs enough, the air conditioner can automatically adjust the set temperature to eliminate users' discomfort according to the temperature regulation preferences from data mining results. Therefore, air conditioners can achieve the goal of meeting users' dynamic thermal comfort needs.

5 Conclusions

1) Although the thermal environment and thermal comfort were both within the acceptable thermal comfort zone, their MTSV values gradually deviated from thermal neutrality and tended to be cooler, which may lead to discomfort.

2) 12 typical posture regulations were captured and divided into 3 categories: head (face) postures, trunk postures, and limb postures. Among them, head (face) postures accounted for approximately 80%, which was the concentrated expression of human body adaptive postures. Most postures frequency decreased after 5 minutes and then remained unchanged, while the head (face) postures gradually increased as time passed, which reflected the increase in human discomfort.

3) The temperature regulations within the set temperature of 25°C to 27°C accounted for nearly 25%, which implied the need for the slight temperature regulations cannot be ignored. Most people (90%) regulated the temperature in the range of 1°C with the frequencies of once or twice, and they preferred to set the temperature up than down. In the first 3 hours, there would be a regulation peak every 20 or 30 minutes, while the regulation decrease after 3 hours.

4) This study can provide a reference for future research on dynamic thermal comfort in the acceptable thermal comfort zone.

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