Determination of the Acceptable Room Temperature Range for Local Cooling

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Abstract: Determination of the acceptable room temperature range is a key problem in satisfactory design of local cooling for energy savings. At the room temperatures ranging from neutral to warm, three sensitive body parts—the face, chest and back—were each exposed to local cooling airflow, where temperatures were 22, 25 and 28°C. Thirty randomly-selected male subjects, dressed in shorts, were exposed to each condition for 30 minutes. Data were collected on their local thermal sensations of each body part, overall thermal sensation, and overall thermal acceptability on voting scales at regular intervals during the exposure. Results show that the non-uniformity of thermal sensation is a key factor affecting thermal acceptability except for overall thermal sensation. A new assessment model for local cooling was proposed. The model shows that face cooling can improve thermal acceptability more than chest or back cooling, and the upper boundary of the acceptable range of room temperature can be shifted from 26°C to 30.5°C when face cooling is provided.

Key words: local cooling; influencing factor; nonuniformity of thermal sensation; overall thermal acceptability

1. INTRODUCTION

Local cooling is increasingly in focus, not only as an alternative to the conventional air conditioning when it is not feasible to control the environment in the entire space, but also as an advanced technology to provide an acceptable environment while using less energy. Thermal comfort and acceptability of local cooling under different room ambient temperatures is a key problem for the well design and application of local cooling.

There have been a number of studies on the effect of local exposure (including local cooling and local heating) on overall thermal acceptability and comfort, mainly concerned with the negative effect of local exposure and performed for establishment of limits for local exposure while maintaining whole body thermal neutral[1~4], and few concerned with the positive effect of local exposure on thermal acceptability and comfort while whole body is warm or cold. Studies performed by Williams et al.[5], Melikov et al.[6], Bauman et al.[7], Brook et al.[8] and Knudsen et al.[9] showed that local heating or cooling could improve subjects' acceptability of the thermal environment. However, the predictive model for the effect of local exposure on thermal acceptability is not available. Zhang[10] derived the relationship between local thermal sensation and overall thermal acceptability at different ambient room temperature, while the results was applicable only to the conditions tested and applies only to seat heating or cooling. Zhang[11] proposed a rule-based overall thermal comfort predictive model using local comfort vote, while two rules are applied to different conditions and no consistent mode is obtained.

The purpose of the present study is to determine the thermal acceptability of local cooling under neutral-warm ambient room environment and to determine the acceptable room temperature range when local cooling is operated.

2. EXPERIMENTAL METHODS

The experiment was carried out in the Department of Building Science at Tsinghua University during the period March 2005 to June 2005.

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2.1 Experimental Design

A personalized ventilation system was used to supply the local cooling airflow and a set of special clothes was used to fix the cooling body surface area (see Fig. 1). Three sensitive body parts: face, chest and back were selected to be cooled locally in the present study. A climate chamber was used to control the ambient room temperature for local cooling. Temperature in the chamber and temperature at the outlet of local airflow could be maintained with a precision of ±0.2°C.

1   2   3

1—Chest cooling 2—Face cooling 3—Back cooling

Fig. 1 Devices for local cooling

Three levels of room temperatures, ranging from neutral to warm, and three levels of local cooling target temperatures (target temperature means the air temperature at the center of cooling body part surface), ranging from neutral to slightly cool, were chosen to be studied (see Table 1).

Tab. 1 Experimental conditions

Factors	Levels
Room temperature (°C)	28，32，35
Target temperature (°C)	22，25，28

The relative humidity was kept constant at 40% and the air speed was less than 0.1m/s in the chamber. The air speed at the outlet of the local cooling airflow was maintained at 1m/s.

2.2 Measurements

Subjects reported their responses twice before local cooling and 16 times while local cooling, at one-minute intervals for six minutes initially and then at two-minute intervals for fourteen minutes and then at five-minute intervals. Overall thermal sensation and local thermal sensation for each of the body parts were reported on the 7-point ASHRAE scale (Fig. 2). A visual-analogue scale indicating acceptability, originally developed to evaluate indoor air quality[12], was used in the present study to assess the whole thermal environment (Fig. 2). Temperature in the room and temperature at the outlet of local airflow were measured and recorded every two seconds during each exposure.

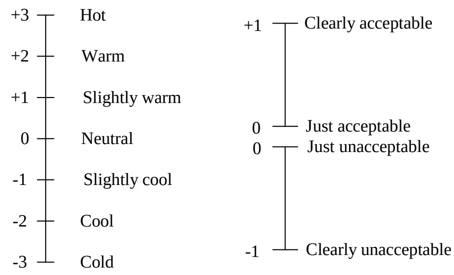

Fig. 2 Voting scales

2.3 Experimental Procedure

Thirty randomly selected chinese male students, dressed in short, with a normal range of age, height and weight participated in the experiment. Each test consisted of half-an-hour pre-conditioning and half-an-hour exposure. The room temperature was maintained constant for each test and no local airflow existed during pre-conditioning. The total duration of each subject's participation was 27 hours. The sequence of presentation was balanced for each subject using Latin squares. Subjects remained sedentary throughout each exposure. Subjects responding 'clearly unacceptable' at any point in time were allowed to terminate the exposure and leave immediately.

3. RESULTS AND DISCUSSION

Shapiro-Wilk's W test was applied and the results show that human responses obtained in all conditions were normally distributed. They were therefore analysed using repeated measure ANOVA and paired-sample t-tests. It was found that human responses reached steady state within 25 minutes during pre-conditioning (p>0.05) and within 20 minutes during exposure (p>0.05) in all conditions. If not mentioned specifically, all responses reported below are steady state responses.

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3.1 Effect of Local Thermal Sensation on Overall Thermal Sensation

Overall thermal sensation is the most important index to assess the acceptability of thermally uniform environment under steady state. Effect of local thermal sensation on overall thermal sensation was analyzed in the present study.

Weighting factor is often applied to evaluate the effect of local thermal sensation of a body part on overall thermal sensation, which is defined as the change of overall thermal sensation when local thermal sensation of a body part changes one unit on thermal sensation voting scale while others' remain constant. However, in the present experiment it was shown that local thermal sensations of the uncooled body parts changed significantly (p<0.01) when local cooling was supplied (7th minute in Fig. 3).

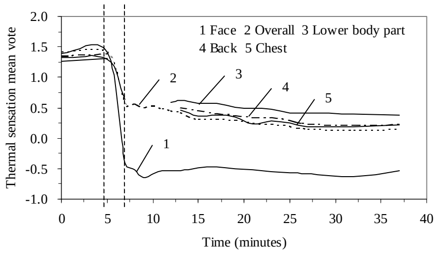

Fig. 3 Change of mean thermal sensation votes with time (room temperature 35°C, target temperature 22°C, no votes between the dashed lines)

In order to integrate the influences of thermal sensation change of all body parts, a new model was proposed, which can be expressed as:

$$\Delta S_O = f_{EO} \Delta S_E \qquad (1)$$

where ΔS_O is the change of overall thermal sensation, ΔS_E is the change of local thermal sensation of the cooling body part, and f_{EO} is the influencing factor of the cooling body part on local thermal sensation of the body part.

According to the new model, influencing factor can be defined as the change of overall thermal sensation when local thermal sensation of the exposed body part changes one unit on the 7-point ASHRAE scale under the condition of single body part cooling. Influencing factor represents the general effect of local cooling on overall thermal sensation, which is not the weighting factor of the cooling body part, but the integrated result of the weighting factors of all body parts.

Influencing factor for face cooling at room temperature 28°C was analyzed and the result is shown in Fig. 4. The change of thermal sensation in the figure means the mean thermal sensation vote during local cooling minus the one during pre-conditioning. A straight line passing origin fits the data well (R^2=0.9). The slope of the line is 0.6, which means that overall thermal sensation changes 0.6 units when face thermal sensation changes one unit, that is to say, the influencing factor of face on overall thermal sensation is 0.6. Fig. 4 also shows the results in three levels of target temperatures and it can be seen that the influencing factor was unaffected by cooling air temperature.

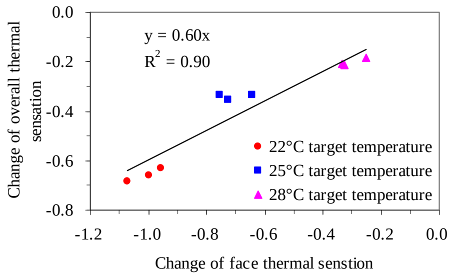

Fig. 4 The influencing factor of face (room temperature 28°C)

Fig. 5 shows the influencing factor for face cooling in all neutral- warm room temperatures. A line fits the data well (R^2=0.92) and the influencing factor of face is unaffected by room temperature.

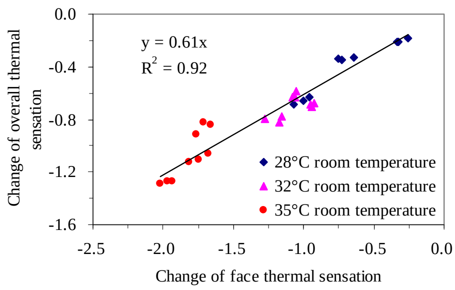

Fig. 5 The influencing factor of face

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The influencing factors of chest and back on overall thermal sensation were analyzed in the same way and the results show that all influencing factors do not change with room or cooling air temperatures significantly. Table 2 shows the results of all influencing factors.

Tab. 2 Influencing factors

Cooling body part	Influencing factor
Face	0.61
Chest	0.47
Back	0.45

It can be seen from Table 2 that face cooling affects overall thermal sensation more than chest or back cooling. Based on influencing factor predictive models of overall thermal sensation were obtained:

$$S_O = f_{EO}(S_E - S_{E0}) + S_{O0} \qquad (2)$$

where S_{O0} and S_{E0} are overall thermal sensation and local thermal sensation of the cooling body part before cooling, S_E is local thermal sensation of the cooling body part while local cooling.

3.2 Non-uniformity of Thermal Sensation

Under thermally uniform environment, the relationship between predicted percentage of dissatisfied and predicted mean vote of thermal sensation was established by Fanger[13] and thermal neutrality corresponds to 5% percentage dissatisfied (see Fig. 6). However, under non-uniform environment, such as the environment with local cooling, overall thermal sensation was found to be apart from percentage dissatisfied, and percentage dissatisfied changed from 5% to 40% while overall thermal sensation remained neutral (see Fig. 6). Overall thermal sensation is not the sole factor influencing thermal acceptability of non-uniform environment.

McNall and Biddison[14] studied thermal sensation and comfort of sedentary persons exposed to asymmetric radiant fields and found that it was 'uneven body temperature' which caused the thermally neutral subjects participating in the Hot Wall series to have a significantly lower probability of feeling comfortable than the subjects in the uniform conditions, where the 'uneven body temperature' means one side of the body feels warmer (or cooler) than the other. 'Uneven body temperature' was inquired by an additional questionnaire in the present experiment and it was found that 97% of the subjects perceived obvious non-uniformity of thermal sensation between different body parts during the non-uniform exposures. Non-uniformity of thermal sensation may be the reason for the scattering of the points on Fig. 6.

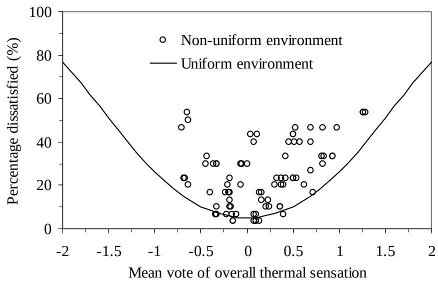

Fig. 6 Relationship between percentage dissatisfied and overall thermal sensation

Considering the strongest feeling of nonuniformity comes from the difference between the coolest and the warmest body part, the maximum thermal sensation difference between body parts was chosen to represent the nonuniformity of thermal sensation. Taking the responses obtained when overall thermal sensation was close to neutral, relationship between the maximum thermal sensation difference between body parts and percentage dissatisfied was analyzed, where the percentage dissatisfied was obtained based on the acceptability vote by calculating the percentage of all subjects marking the scale in the unacceptable range (from –1 to 0) in each condition. The results are shown in Fig. 7. More thermal sensation difference, more people feel dissatisfied, and a second-order polynomial curve fits the data well (R^2=0.88), regardless which body part is cooled.

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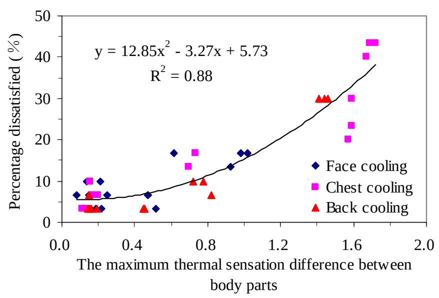

Fig. 7 Percentage dissatisfied as a function of the maximum thermal sensation difference between body parts while whole body was close to neutral

Fig. 7 can explain the discrepancy between overall thermal neutrality and 5% percentage dissatisfied in the non-uniform environment. Nonuniformity of thermal sensation is another important factor affecting thermal acceptability.

3.3 Assessment Model for Non-uniform Environment

Subjects evaluate non-uniform environment based on their perception of overall thermal sensation and nonuniformity of thermal sensation between body parts. As the two kinds of perception are independent, the general percentage dissatisfied with non-uniform environment can be reasonably expressed as the sum of the effects of the two perceptions:

$$PD = PD_1 + PD_2 \qquad (3)$$

where PD is the general percentage dissatisfied with non-uniform environment, PD_1 is the uniform term and PD_2 is the non-uniform term.

The uniform term is a function of overall thermal sensation S_O, and the function was obtained by an analogy from the results of uniform environment:

$$PD_1 = 100 - 95e^{-(0.03353 S_O{}^4 + 0.2179 S_O{}^2)} \qquad (4)$$

The non-uniform term is a function of the maximum thermal sensation difference between body parts S_D, and the function was obtained by the regression of the experimental data obtained in the present study (see Fig. 8):

$$PD_2 = 7.27 S_D{}^2 + 6.43 S_D \qquad (5)$$

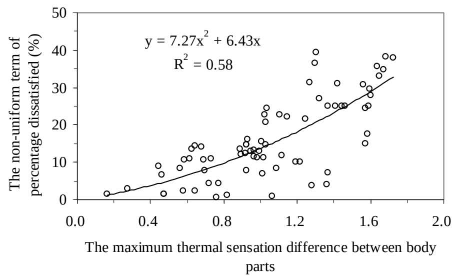

Fig. 8 The non-uniform term of percentage dissatisfied as a function of the maximum thermal sensation difference between body parts

3.4 Predictive Model of Human Responses to Local Cooling

The effect of local cooling on nonuniformity of thermal sensation was analyzed using influencing factor method and the result shows that the influencing factor of face, chest and back on the maximum thermal sensation difference between body parts is -0.42, -0.83 and -0.78 respectively. Predictive model of the maximum thermal sensation difference between body parts was obtained based on the influencing factors:

$$S_D = f_{ED}(S_E - S_{E0}) + S_{D0} \qquad (6)$$

where S_{D0} and S_D are the maximum thermal sensation difference between body parts before and while local cooling, f_{ED} is the influencing factor of the cooling body part on the maximum thermal sensation difference between body parts.

Using equations (2~5), percentage dissatisfied with non-uniform environment can be predicted and human responses to local cooling can be predicted by the initial whole body thermal state and local thermal sensation of the cooling body part.

3.5 Comparison of Different Body Part Cooling

Taking room temperature 35°C as an example, human responses to face, chest and back cooling are predicted by the models. Fig. 9 shows the result for face cooling. When the intensity of face cooling is enhanced, overall thermal sensation decreases and the maximum thermal sensation difference between body parts increases. As the influencing factor of face on overall thermal sensation is 0.61 and the one on the

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maximum thermal sensation difference between body parts is –0.42, the change of overall thermal sensation is greater than the change of nonuniformity of thermal sensation, resulting in a significant improvement of thermal acceptability.

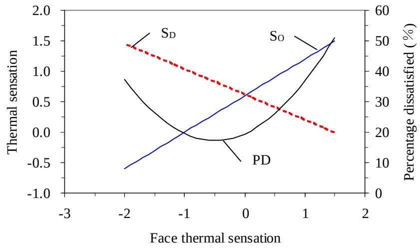

Fig. 9 Human responses (overall thermal sensation SO, the maximum thermal sensation difference between body parts SD, and percentage dissatisfied PD) to face cooling

Fig. 10 shows the result for chest cooling. As the influencing factor of chest on overall thermal sensation is 0.47 and the one on the maximum thermal sensation difference between body parts is –0.83, the change of nonuniformity of thermal sensation is greater than the change of overall thermal sensation, resulting in a small improvement of thermal acceptability. The result for back cooling is similar with the one for chest cooling.

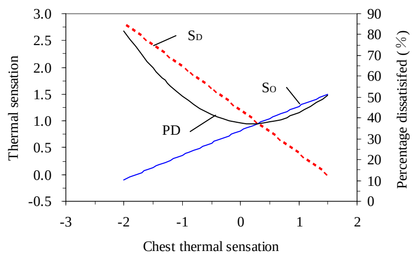

Fig. 10 Human responses (overall thermal sensation SO, the maximum thermal sensation difference between body parts SD, and percentage dissatisfied PD) to chest cooling

The influencing factors on overall thermal sensation and nonuniformity of thermal sensation determine the general effect of local cooling. If the absolute value of the influencing factor on overall thermal sensation is much bigger than the one on nonuniformity of thermal sensation, local cooling can improve thermal acceptability significantly.

3.6 Acceptable Room Temperature Range for Face Cooling

ASHRAE standards (1992) take 80% acceptability as the criterion, which includes 10% overall thermal discomfort and 10% local thermal discomfort. When local cooling is applied, overall thermal discomfort can be decreased while local thermal discomfort is increased, and the criterion does not work under this condition. A new criterion was proposed as the sum of overall and local thermal discomfort less than 20%.

Percentage dissatisfied for face cooling at different ambient room temperatures in summer conditions was predicted and shown in Fig. 11. According to the new criterion, the upper boundary of the acceptable range of room temperature can be shifted from 26° C to 30.5°C while face cooling is provided. The change of the acceptable temperature range could reduce cooling load of buildings and save energy.

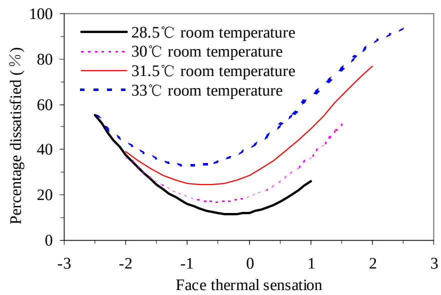

Fig. 11 Percentage dissatisfied as a function of face thermal sensation at different room temperatures

4. CONCLUSIONS

The thermal acceptability of local cooling under neutral-warm ambient room environment was studied in the present experiment and the following conclusions can be drawn:

1. A new influencing factor method was proposed based on the fact that local thermal sensations of the uncooled body parts changed with local cooling. The influencing factor of each body part

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is unaffected by room or cooling air temperatures. Based on influencing factor predictive models of overall thermal sensation were obtained.

2. Nonuniformity of thermal sensation is an important factor affecting thermal acceptability of non-uniform environment. Taking the maximum thermal sensation difference between body parts to represent nonuniformity of thermal sensation, a new assessment model of non-uniform environment was proposed.
3. The influencing factors on overall thermal sensation and nonuniformity of thermal sensation determine the general effect of local cooling. Face cooling can improve thermal acceptability more than chest or back cooling and the upper boundary of the acceptable room temperature range can be shifted from 26°C to 30.5°C when face cooling is provided.

5. ACKNOWLEDGEMENTS

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