COMFORT MODEL FOR LOCAL COOLING

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ABSTRACT

At room temperatures ranging from 28 to 35°C, three sensitive body parts were each exposed to local cooling airflow. Dressed in shorts, 30 randomly selected male subjects were exposed to each condition for 30 minutes and reported their local thermal sensations of all body parts, overall thermal sensation, thermal acceptability and comfort on voting scales at regular intervals. Local cooling affected local thermal sensations of the uncooled body parts significantly, based on which an influencing factor method was proposed and the overall thermal sensation model for local cooling was established. Non-uniformity of thermal sensation affected overall thermal acceptability significantly. Overall thermal acceptability and comfort were highly correlated under uniform and non-uniform conditions. Comfort model for local cooling was proposed and it shows by the model that the upper boundary of the acceptable room temperature range can be shifted from 26°C to 30.5°C when face cooling is provided.

KEYWORDS

Comfort model, local cooling, influencing factor, non-uniformity of thermal sensation

INTRODUCTION

Local cooling is increasingly in focus as an advanced technology to provide an acceptable environment while using less energy. The effect of local cooling on human responses, including thermal sensation and comfort, is the key problem in the studies on local cooling.

Weighting factor method is commonly used to study the effect of local cooling on overall thermal sensation. Ingersoll et al. (1992) proposed to use the respective surface area of each body part as its weighting factor, however, Hagino and Hara (1992) found that the whole body thermal sensation was governed by local thermal sensation of certain small areas of the body that were exposed to direct airflow or solar radiation in the passenger compartment in automobile, instead of large area of the body. Zhang (2003) found that as local sensation diverged from that of the rest of the body, weighting factor became larger, and certain body segments, such as chest, back and pelvis had larger weighting factors and dominated the influence on overall sensation, while hand and foot had small weighting factors. Li (2004) reported that weighting factor changed with the intensity of local stimulus, and the weighting factor of head was biggest. Weighting factor as a key index evaluating the effect of local thermal sensation on overall thermal sensation has been widely accepted, however, which body part has large weighting factor and what variables affect weighting factor remain inconsistent.

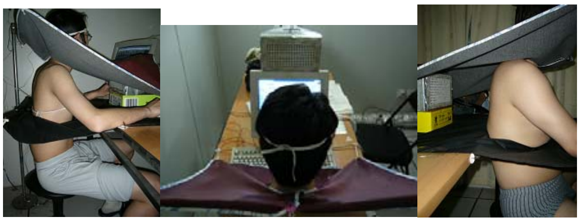
There have been a number of studies on the effect of local exposure (include cooling and heating) on overall thermal acceptability and comfort, mainly concerned with the negative effect of local exposure while maintaining whole body thermal neutral (ASHRAE Handbook, 2001), and few concerned with the positive effect of local exposure on comfort while whole body is warm or cold. Studies performed by Melikov et al. (1994), Bauman et al. (1998), Brook et al. (1999) and Knudsen et al.(2005) showed that local exposure 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 (2007) 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 (2003) proposed a rule-based overall thermal comfort predictive model using local comfort vote, while two rules were applied to different conditions and no consistent mode was obtained.

The purpose of the present study is to investigate quantitatively the effect of local cooling on thermal sensation and comfort and to develop the comfort model for local cooling.

EXPERIMENTAL METHODS

Experimental design

The experiment was carried out in the Department of Building Science at Tsinghua University during the period March 2005 to June 2005. 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 Figure 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 was maintained with a precision of ±0.2°C.



Chest cooling Face cooling Back cooling

Figure 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). 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.

Table 1 Experimental conditions

ROOM TEMPERATURE (°C)	**TARGET TEMPERATURE (°C)**
28，32，35	22，25，28

Measurements

Subjects reported their responses twice before local cooling and 16 times while local cooling, at one-minute intervals for six minutes 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 (including face, chest, back and lower body part) were reported on the 7-point ASHRAE scale (Figure 2). A thermal comfort scale developed by Zhang (2003) was applied in the present study to force subjects to make a clear determination about whether their perceived state falls in the category of “Comfortable” or “Uncomfortable” (Figure 2). Temperature in the room and temperature at the outlet of local airflow were measured and recorded every two seconds during each exposure.

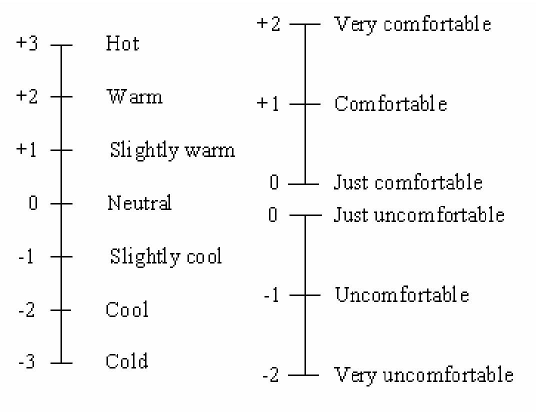


Figure 2 Voting scales

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 ‘very uncomfortable’ at any point in time were allowed to terminate the exposure and leave immediately.

RESULTS

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 local cooling ($p>0.05$) in all conditions. If not mentioned specifically, all responses reported below are steady state responses.

Influencing factor method

Taking face cooling with room temperature 35°C and target temperature 22°C as an example, Figure 3 shows the change of mean thermal sensation votes with time. When face cooling was supplied (7th minute in the figure), not only face thermal sensation and overall thermal sensation decreased rapidly, but also local thermal sensations of the uncooled body parts, including chest, back and lower body part, changed obviously. The responses were tested for significance using paired-sample t-tests and the results show that local thermal sensations of the uncooled body parts changed significantly with local cooling($p<0.05$).

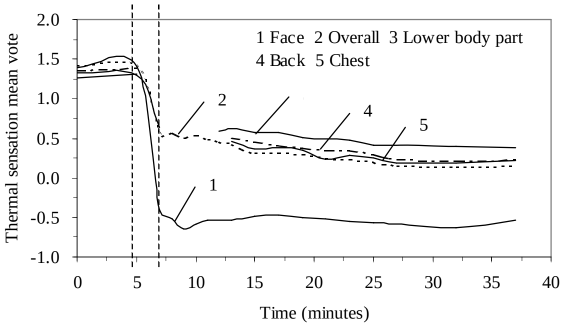


Figure 3 Change of mean thermal sensation votes with time (face cooling, room temperature 35°C, target temperature 22°C, no votes between the dashed lines)

Correlation between thermal sensations of different body parts was analyzed using collinearity diagnostics and the results show that high collinearity exists in most cases (tolerance<0.1). As repeated-measures experimental design, which is often used in thermal comfort experiment, was adopted in the present study, sphericity assumption was tested and the results show that the autocorrelation in the responses is significant ($p<0.05$). Collinearity and autocorrelation violate the independency of the data and may result in unreasonable results using weighting factor method, which can be expressed as:

$$TS_O = w_1TS_1 + w_2TS_2 + ... + w_nTS_n \qquad (1)$$

where TS_O is overall thermal sensation, TS_i is local thermal sensation of body part i and w_i is weighting factor of the body part i.

To solve the problem, a new method was proposed, which can be expressed as:

$$\triangle TS_O = f_{EO}\triangle TS_E \qquad (2)$$

where $\triangle TS_O$ is the change of overall thermal sensation, $\triangle TS_E$ is the change of local thermal sensation of the cooling body part, and f_{EO} is the regression coefficient.

The effect of collinearity and autocorrelation are removed using the new method. A new term 'influencing factor' is proposed for f_{EO} which is defined as the change of overall thermal sensation when local thermal sensation of the cooling 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, while weighting factor represents the importance of local thermal sensation of a single body part in the process of integration of overall thermal sensation.

Overall thermal sensation model for local cooling

Influencing factor for face cooling was analyzed using the influencing factor method and the result is shown in Figure 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 ($R^2>0.9$) and the slope represents the influencing factor of face on overall thermal sensation. It can be seen that the influencing factor was unaffected by either cooling air temperature (Figure 4) or room temperature (Figure 5).

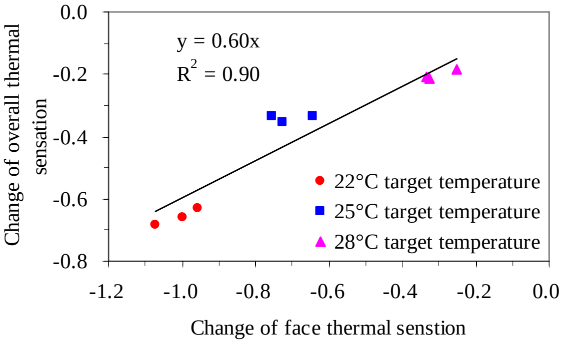


Figure 4 The influencing factor for face cooling at room temperature 28°C

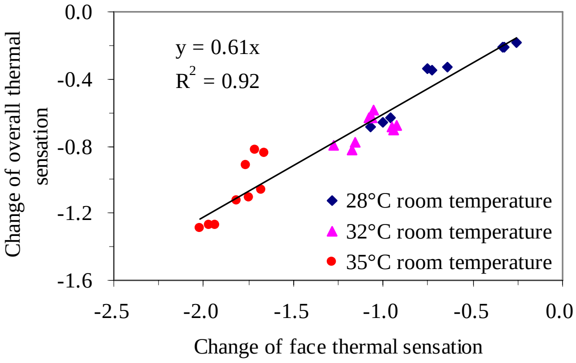


Figure 5 The influencing factor for face cooling in all conditions

The influencing factors of chest and back on overall thermal sensation and the influencing factors of the cooling body parts on local thermal sensations of the uncooled body parts were analyzed in the same way and the results are listed in Table 2.

Table 2 Influencing factors ($R^2>0.63$)
(to be continued)

COOLING BODY PART	FACE THERMAL SENSATION	CHEST THERMAL SENSATION
Face	1	0.54
Chest	0.16	1
Back	0.18	0.3

(continued)

COOLING BODY PART	BACK THERMAL SENSATION	LOWER BODY PART THERMAL SENSATION	OVERALL THERMAL SENSATION
Face	0.57	0.43	0.61
Chest	0.4	0.31	0.47

Back	1	0.3	0.45

It can be seen from Table 2 that face cooling affects overall thermal sensation and local thermal sensations of the uncooled body parts more than chest or back cooling. The impact of chest cooling on back thermal sensation is close to the impact of back cooling on chest thermal sensation. However, the impact of chest or back cooling on face thermal sensation is much less than the impact of face cooling on chest or back thermal sensation.

Based on the influencing factor, an overall thermal sensation model for local cooling was obtained:

$$TS_O = f_{EO}(TS_E - TS_{EI}) + TS_{OI} \qquad (3)$$

where TS_{OI} and TS_{EI} are the initial overall thermal sensation and local thermal sensation of the cooling body part before local cooling, TS_E is local thermal sensation of the cooling body part while local cooling.

If the initial whole body thermal state and local thermal sensation of the cooling body part are known, overall thermal sensation can be predicted using the model. Similarly local thermal sensations of the uncooled body parts can be predicted by the corresponding influencing factor.

Non-uniformity of thermal sensation

Overall thermal sensation is the most important index to evaluate thermal comfort under uniform environment under steady state, however, overall thermal sensation was found to be apart from thermal comfort while local cooling was supplied, and thermal comfort changed from -0.02 to 0.97 while overall thermal sensation remained neutral (see Figure 6). Overall thermal sensation is not the sole factor influencing thermal comfort under thermal environment with local cooling.

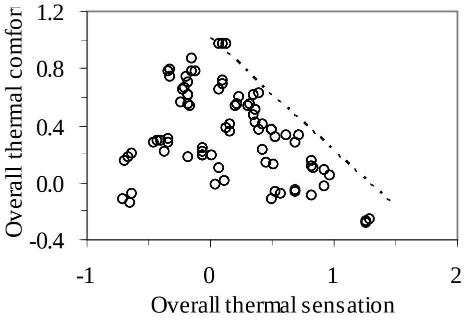


Figure 6 Overall thermal comfort as functions of overall thermal sensation under the conditions with local cooling (hollow dot) and without local cooling (dashed line)

The survey in the present experiment shows that most of the subjects perceive obvious non-uniformity of thermal sensation between body parts during local cooling. Under this circumstance, they felt uncomfortable with the whole environment even when they felt neutral for whole body thermal sensation. Considering the strongest feeling of non-uniformity 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 non-uniformity of thermal sensation. It can be seen from Figure 7 that more non-uniformity of thermal sensation, more people feel uncomfortable while their whole body was kept neutral. A linear function fits the data very well (R^2=0.88). Non-uniformity of thermal sensation can explain the breakage of the relationship between overall thermal sensation and comfort.

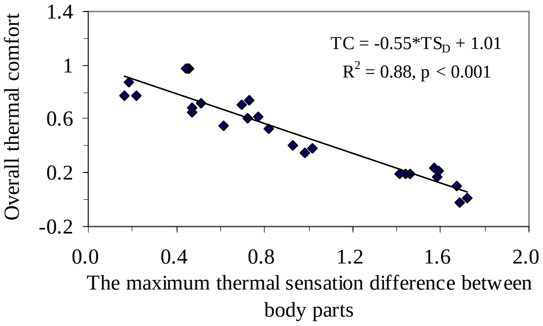


Figure 7 Overall thermal comfort (TC) as a function of the maximum thermal sensation difference between body parts (TS_D) when in overall thermal neutrality

Comfort model for local cooling

Subjects evaluate thermal environment with local cooling based on their perceptions of overall thermal sensation and non-uniformity of thermal sensation. As the two perceptions are independent, the overall thermal comfort with thermal environment with local cooling can be reasonably expressed as the sum of the effects of the two perceptions:

$$TC = TC_1 + TC_2 \qquad (4)$$

where TC is the overall thermal comfort, TC_1 is the uniform term and TC_2 is the non-uniform term.

The uniform term is a function of overall thermal sensation TS_O, and the function was obtained by linear regression of the data obtained under the conditions without local cooling (see Figure 8):

$$TC_1 = -0.79\ TS_O + 1.01 \qquad (5)$$

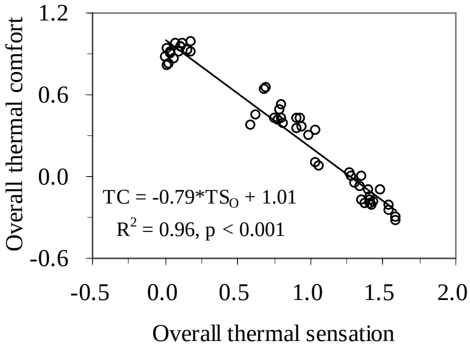


Figure 8 Overall thermal comfort (TC) as a function of the maximum thermal sensation difference between body parts (TS_D) when in overall thermal neutrality

The non-uniform term is a function of the maximum thermal sensation difference between body parts TSD. The function was obtained by linear regression of the data under the conditions with local cooling while whole body thermal sensation closes to neutral (see Figure 7):

$$TC_2 = -0.55\ TS_D \qquad (6)$$

where TS_D can be expressed further by using influencing factor method:

$$TS_D = f_{ED}(TS_E - TS_{EI}) + TS_{DI} \qquad (7)$$

where TS_{DI} is the initial maximum thermal sensation difference between body parts before local cooling and f_{ED} is the influencing factor of the exposed body part on the maximum thermal sensation difference between body parts, which is -0.42 for face, -0.83 for chest and -0.78 for back by analyzing the responses obtained in the present study.

Combing equations (3)~(7), a comfort model for local cooling was establishe as below:

$$TC = -0.79\ (f_{EO}(TS_E - TS_{EI}) + TS_{OI}) - 0.55\ (f_{ED}(TS_E - TS_{EI}) + TS_{DI}) + 1.01 \qquad (8)$$

The model can be used for prediction of thermal comfort under thermal environment with local cooling of face, chest or back.

CONCLUSIONS

The effect of local cooling on human responses was studied in the present experiment and the following conclusions were 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. Based on the influencing factor a overall thermal sensation model for local cooling was obtained.
2. Non-uniformity of thermal sensation between body parts is an important factor affecting thermal comfort under thermal environment with local cooling.
3. Taking the maximum thermal sensation difference between body parts to represent non-uniformity of thermal sensation, a comfort model for local cooling was established.

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