RELATIONSHIPS BETWEEN OVERALL THERMAL SENSATION, ACCEPTABILITY AND COMFORT

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ABSTRACT
Thermal sensation, acceptability and comfort are the important responses while evaluating the quality of thermal environment. Experimental investigations into the relationships between these responses were performed separately under uniform and non-uniform conditions that produced by local cooling. Thirty male Chinese subjects in college age participated the experiment and reported their local thermal sensation of each body part, overall thermal sensation, acceptability and comfort. Under uniform conditions, overall thermal sensation, acceptability and comfort are correlated closely. Acceptable range runs from neutral to 1.5 (midpoint between ‘Slightly Warm’ and ‘Warm’) on thermal sensation scale and contains all comfortable and slightly uncomfortable votes on thermal comfort scale. Under non-uniform conditions overall thermal acceptability and comfort are correlated closely. However, overall thermal sensation is apart from acceptability and comfort and non-uniformity of thermal sensation was found to be the reason for the breakage. Combining the effects of overall thermal sensation and non-uniformity of thermal sensation, a new thermal acceptability model was proposed and the model is validated in uniform and non-uniform conditions over a wide range of whole body thermal state from neutral to slightly warm.

KEYWORDS
Overall thermal sensation, Overall thermal acceptability, Overall thermal comfort; Non-uniformity of thermal sensation

INTRODUCTION
Recently with the requirements of energy saving, more and more attentions were paid on the research of thermally non-uniform environment. Assessment of the non-uniform environment is a highlighted problem for the well-design of non-uniform environment in buildings.

For the assessment of uniform and steady thermal environment, the known indices, such as PMV, ET* and SET, which predict human thermal sensation by environmental parameters and personal information, are widely accepted. However, there is no index accepted universally to evaluate thermally non-uniform environment and overall (whole body) thermal sensation (Burch et al. 1991, Hagino and Hara 1992, Li 2004, Hodder et al. 1998), overall thermal acceptability (Melikov et al. 1994, Zhang et al. 2007, Melikov 2004, Gong et al. 2005) and overall thermal comfort (Schlegel and McNall 1968, Brooks and Parsons 1999, Zhang 2003, Sakoi et al. 2005) were used separately by different authors. It would be useful to understand the relationship between overall thermal sensation, acceptability and comfort under non-uniform conditions.

The relationship between thermal sensation and acceptability was firstly clarified by Fanger (1970), who defined the dissatisfied as those who vote ‘Cool’ or ‘Cold’, ‘Warm’ or ‘Hot’ based on the experimental results by Gagge et al. (1967). This definition was confirmed by Berglund (1979) through
comparison with the responses obtained by directly asking subjects whether they find the thermal conditions acceptable or unacceptable. As the relationship was derived and confirmed under uniform conditions, its validity under non-uniform conditions remains untested.

The relationship between thermal comfort and acceptability was investigated by Berglund (1979). He compared the effect of temperatures that deviate from those of optimum comfort assessed by percent comfortable (Gagge and Nevins 1976) with the one by thermal acceptability (Berglund and Gonzalez 1978) and found that they were quite similar, which indicates that the thermal comfort votes falling in comfortable or slightly uncomfortable range were perceived by the subjects as acceptable. The comparison was conducted under uniform environment and the one for non-uniform environment remains vacant.

The known relationships between thermal sensation, acceptability and comfort were qualitative and derived in uniform environment. The purpose of the present study was to investigate quantitatively the relationships between overall thermal sensation, acceptability and comfort under uniform and non-uniform environment and to develop a new thermal acceptability model applicable to both environments.

**EXPERIMENTAL METHODS**

The experiment was carried out in the climate chamber in Tsinghua University. The chamber was used to supply a thermally uniform ambient environment and the temperature in the chamber could be maintained with a precision of ±0.2°C. Personalized ventilation system was used to produce non-uniform environment by supplying local cooling airflow to three sensitive segments of human body: face, chest and back separately.

Three room temperatures, ranging from neutral to warm, were chosen and for each room temperature, three 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 studied in the present experiment (Table 1). Relative humidity was kept at 40%, and air velocity was less than 0.1m/s in the room air. Air velocity at the outlet of cooling airflow was maintained at 1m/s.

<table>
<thead>
<tr>
<th>Room temperature (°C)</th>
<th>28, 32, 35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target temperature (°C)</td>
<td>22, 25, 28</td>
</tr>
</tbody>
</table>

Each test consisted of half-an-hour exposure to uniform condition and half-an-hour exposure to non-uniform condition. Thirty randomly selected Chinese college-age students, dressed in short, with a normal range of height and weight participated in the experiment of all conditions and the total duration for each subject was 27 hours. The sequence of presentation was balanced among subjects. Subjects remained sedentary throughout each exposure. Conversation was permitted but the subjects were not allowed to exchange views concerning the thermal environment.

Subjects reported their local thermal sensation of each body part, overall thermal sensation, overall thermal acceptability and overall thermal comfort simultaneously at each voting time and three times in the last 10 minutes for each exposure. Thermal sensations were reported on ASHRAE 7-point scale (Fig. 1a). A visual-analogue scale indicating acceptability, originally developed to evaluate indoor air quality by Gunnarsen and Fanger (1992), was used in the present study (Fig. 1b). 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” (Fig. 1c).
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 analyzed using repeated measure ANOVA and paired-sample t-tests. It was found that human responses reached steady state within 20 minutes during each exposure (p>0.05). If not mentioned specifically, all responses reported below are steady state responses.

Responses to the uniform conditions

Human responses to the uniform exposures were analyzed and the results are shown in Fig. 2-3. Each point in the Fig.s represents the mean vote of all subjects’ responses for each condition. It can be seen that a straight line fits the data well for each Fig. (R^2>0.95).

Fig. 2. Overall thermal acceptability, TA, and overall thermal comfort, TC, as functions of overall thermal sensation, TS, under the uniform conditions

\[ \text{TA} = -0.41 \times \text{TS} + 0.58 \]
\[ R^2 = 0.96, p < 0.001 \]

\[ \text{TC} = -0.79 \times \text{TS} + 1.01 \]
\[ R^2 = 0.96, p < 0.001 \]
Under the uniform conditions, overall thermal sensation, acceptability and comfort are correlated with each other closely. Thermal sensation mean vote of 1.5 corresponds to thermal acceptability mean vote of 0 and thermal comfort mean vote of -0.2, that is to say, acceptable range runs from neutral to 1.5 on thermal sensation scale and contains all comfortable and slightly uncomfortable votes on thermal comfort scale, which confirms the relationships found before under uniform conditions.

**Responses to the non-uniform conditions**

Human responses to the non-uniform exposures were analyzed and the results are shown in Fig. 4-5. Each point represents the mean vote of all subjects’ responses for each condition. Compared with the linear relationship obtained in the uniform conditions, no linear relationships exist between overall thermal sensation and acceptability and comfort under the non-uniform conditions (see Fig. 4). Subjects feel more uncomfortable and unacceptable with the non-uniform environment than the uniform one while their overall thermal sensations are the same. The linear relationship between overall thermal acceptability and comfort is retained well ($R^2=0.98$) in the non-uniform conditions (see Fig. 5) and the function is very similar with the one obtained under the uniform conditions.

**Fig. 3.** Overall thermal acceptability as a function of overall thermal comfort under the uniform conditions

**Fig. 4.** Overall thermal acceptability and comfort as functions of overall thermal sensation under the non-uniform conditions
The scattering of the points on Fig. 4 indicates that it is difficult to define acceptable or comfortable range only by whole body thermal sensation vote for that each thermal sensation vote corresponds to a wide range of thermal acceptability and comfort. For instance, thermal neutrality corresponds to the acceptability range of (0.07, 0.54) and the comfort range of (-0.02, 0.97). Thus the relationship proposed by Fanger is not suitable for non-uniform environment. Except for overall thermal sensation, there should be other factors influencing thermal acceptability and comfort with non-uniform environment.

Non-uniformity of thermal sensation
McNall and Biddison (1970) 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. 4.

Considering the strongest feeling 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. Taking the responses obtained when subject's whole body thermal sensation vote close to neutral (mean vote of overall thermal sensation falls in (-0.2, +0.2)), the relationships between the maximum thermal sensation difference between body parts and overall thermal comfort and acceptability were analyzed and the results are shown in Fig. 6-7. When the non-uniformity is small, subjects perceive the non-uniform environment the same comfortable and acceptable with the uniform one. With the increase of non-uniformity, overall thermal comfort and acceptability go down apparently and the tendency is linear ($R^2>0.88$). Non-uniformity of thermal sensation explains well the breakage of the relationship between overall thermal sensation and acceptability and comfort.
A new thermal acceptability model

Subjects evaluate thermally non-uniform environment based on their perceptions of overall thermal sensation and non-uniformity of thermal sensation. Supposing these two perceptions are independent from each other, a new thermal acceptability model was proposed:

\[ TA = TA_1 + TA_2 \]  

(1)

where \( TA \) is the overall thermal acceptability, \( TA_1 \) is the uniform term and \( TA_2 \) is the non-uniform term.

The uniform term is a function of overall thermal sensation \( TS \), and the function was obtained by linear regression of the data obtained under the uniform conditions (see Fig. 2):

\[ TA_1 = -0.41*TS + 0.58 \]  

(2)

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 non-uniform conditions while whole body thermal sensation closes to neutral (see Fig. 6):

\[ TA_2 = -0.27*TSD + 0.57 \]  

(3)

In order to validate the new thermal acceptability model for the non-uniform conditions that vary from neutrality, all responses obtained in the present experiment were collected and multiple linear regression was performed.
Table 2. Coefficientsa

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>t</th>
<th>Sig.</th>
<th>Collinearity Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
<td></td>
<td>Tolerance</td>
</tr>
<tr>
<td>1 (Constant)</td>
<td>0.607</td>
<td>0.014</td>
<td></td>
<td>43.601</td>
<td>0.000</td>
</tr>
<tr>
<td>TS</td>
<td>-0.398</td>
<td>0.013</td>
<td>-0.971</td>
<td>-30.473</td>
<td>0.000</td>
</tr>
<tr>
<td>TS D</td>
<td>-0.209</td>
<td>0.012</td>
<td>-0.563</td>
<td>-17.666</td>
<td>0.000</td>
</tr>
</tbody>
</table>

a. Dependent Variable: TA

As Table 2 shows, TS is independent from TS D (tolerance>0.8) and TS and TS D affect TA significantly (p<0.001) and the linear regression function is very similar with the new thermal acceptability model. In order to justify the validity of the model in quantity, the predicted overall thermal acceptability calculated from the actual overall thermal sensation and non-uniformity of thermal sensation was compared with the actual overall thermal acceptability (see Fig. 8). The responses in neutral-cool range were not included in the analysis for the equation (2) was obtained in neutral-warm conditions.

![Fig. 8. Validation of the new thermal acceptability model in the non-uniform conditions that vary from neutrality](image)

It can be seen that the predicted values is highly correlated with the measured values ($R^2 > 0.91$, $p < 0.001$). The new thermal acceptability model is suitable for both neutral and slightly warm, uniform and non-uniform conditions. Subjects evaluate the acceptability of thermal environment from two aspects separately: whole body thermal sensation and non-uniformity of thermal sensation. Whole body thermal sensation affects thermal acceptability in the same way under uniform environment and non-uniform environment. The effect of non-uniformity of thermal sensation on thermal acceptability obtained under thermal neutral conditions is valid for warm conditions. The acceptable range according to the new thermal acceptability model can be expressed as:

$$ -0.41TS + 0.58 - 0.27TS_D > 0 $$

CONCLUSIONS

The relationships between overall thermal sensation, acceptability and comfort under uniform and non-uniform conditions were studied in the present experiment and the following conclusions can be drawn:

1. Overall thermal acceptability and comfort are highly correlated and the thermal comfort votes falling
in comfortable or slightly uncomfortable range are perceived as acceptable under uniform and non-uniform conditions.

2. Overall thermal sensation is correlated with thermal acceptability and comfort closely and acceptable range runs from neutral to 1.5 (midpoint between slightly warm and warm) on thermal sensation scale under uniform environment. However, overall thermal sensation is apart from the other two responses and thermal neutrality does not mean thermal comfort any more under non-uniform environment.

3. Non-uniformity of thermal sensation is the reason for the breakage of the relationship between overall thermal sensation and acceptability and comfort.

4. Combining the effects of overall thermal sensation and non-uniformity of thermal sensation, a new thermal acceptability model is proposed. The model is applicable to uniform and non-uniform conditions over a wide range of whole body thermal state from neutral to slightly warm.

ACKNOWLEDGEMENTS

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REFERENCES