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Relationship between thermal sensation and comfort in non-uniform and dynamic environments

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A B S T R A C T

The relationship between thermal sensation and thermal comfort was studied experimentally under uniform and non-uniform, steady and dynamic conditions separately. Thirty subjects participated in all the experiment and reported their thermal sensation and thermal comfort simultaneously. Thermal sensation and comfort are found to be correlated closely under steady and uniform conditions and the comfort zone of thermal sensation vote in warm side is (0, 1.25). Under steady and non-uniform conditions thermal sensation change with space is found to be an important factor determining thermal comfort. Combining the effects of overall thermal sensation and thermal sensation change with space, a thermal comfort model for steady conditions is proposed. Under dynamic conditions, thermal sensation change with time affects thermal comfort significantly.

1. Introduction

Recently with the rising demand of energy conservation, more and more attentions were paid on the studies of thermally non-uniform and dynamic environments. Compared with the traditional uniform and steady environment, non-uniform environment produced by personalized ventilation [1,2], task air-conditioning [3–5] or heated/cooled seat [6] can thermally satisfy occupants within a much wider room air temperature range, resulting great potentials of energy saving. The fact that human body is more sensitive to cold than warm is confirmed by several well-organized experiments [7,8] and the resulting benefit for energy conservation by providing a dynamic environment with fluctuating air temperature [9] or air movement [10,11] in warm environment is reported. Human responses to non-uniform and dynamic environments are different from the ones to uniform and steady environments and proper assessment of thermal environment is the basis for well design of non-uniform or non-steady environments in buildings.

Thermal sensation indices, such as PMV, ET* and SET, which can predict human thermal sensation by environmental parameters and personal information, are widely accepted for the assessment of thermally uniform and steady environments based on the known relationship between thermal sensation and thermal comfort. The relationship was first investigated by Gagge et al. [7], who collected and analyzed the human responses to various uniform environments with temperatures changing from 12 to 48 °C and found that the sensory domain "Comfortable" may extend from a temperature sense of "Neutral" up to reports of "Cool" or "Warm". The relationship was then adopted by Fanger [12] to build up the bridge between PMV and PPD and worked well as the basis for the evaluation of steady and uniform environment.

Only few studies are focused on the relationship between thermal sensation and comfort under non-uniform or dynamic environment, and overall (whole body) thermal sensation [11,13–15] and overall thermal comfort [16,17] were used separately by different researchers to assess non-uniform and non-steady environments. Zhang [18] proposed an overall thermal comfort model for non-uniform and dynamic conditions based on human response of local thermal comfort, which is related to local thermal sensation and overall thermal sensation. The model is a rule-based model with two rules for different conditions and no consistent mode is obtained for all conditions. The authors [19] studied the relationship between overall thermal sensation, comfort and acceptability under uniform and non-uniform conditions and mentioned non-uniformity of thermal sensation affected thermal comfort significantly in non-uniform conditions. However, no results were obtained in dynamic conditions. The purpose of the present study was to investigate the relationship between thermal sensation and thermal comfort under non-uniform and dynamic environments.

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2. Experimental methods

The experiment was carried out from March to June in 2005. A climate chamber in the Department of Building Science at Tsinghua University was used to maintain a steady and thermally uniform environment and the temperature inside the chamber was maintained with a precision of ±0.2 °C. Personalized ventilation, which attains many attentions due to its high performance on indoor environmental quality, great potential of energy saving and broad applications in both non-uniform environment and dynamic environment [11], was used in the present study to produce non-uniform and dynamic environments by supplying local cooled airflow. Face, as one of the most sensitive segments of human body and the most frequently exposed area while applying personalized ventilation, was locally cooled in the experiment.

Each test consisted of half-an-hour exposure to uniform conditions and half-an-hour exposure to non-uniform conditions. The ambient room temperature was maintained the same and local cooled airflow was supplied only when the exposure to non-uniform conditions started. Three room temperatures, ranging from neutral to warm, were chosen and for each room temperature, three local cooled target temperatures (target temperature means the air temperature at the center of face 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 0.1 m/s in the room air. Air velocity at the outlet of cooling airflow was maintained at 1 m/s.

Thirty randomly selected chinese college-age subjects, dressed in short, with a range of height from 163 to 182 cm and weight from 55 to 86 kg participated in all the experiment and the total duration for each subject was 27 h. 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 sensations of face, cheek, back and lower body part, overall thermal sensation and overall thermal comfort simultaneously at each voting time. During exposure to uniform conditions, subjects voted twice in the last 5 min. During exposure to non-uniform conditions, subjects voted at 1-min intervals for 6 min, and then 2-min intervals for 14 min and then at 5-min intervals. Thermal sensations were reported on ASHRAE 7-point scale (Fig. 1a). A thermal comfort scale developed by Zhang [18] was applied in the present study to force subjects to make a clear determination about whether their perception falls in the category of “Comfortable” or “Uncomfortable” (Fig. 1b).

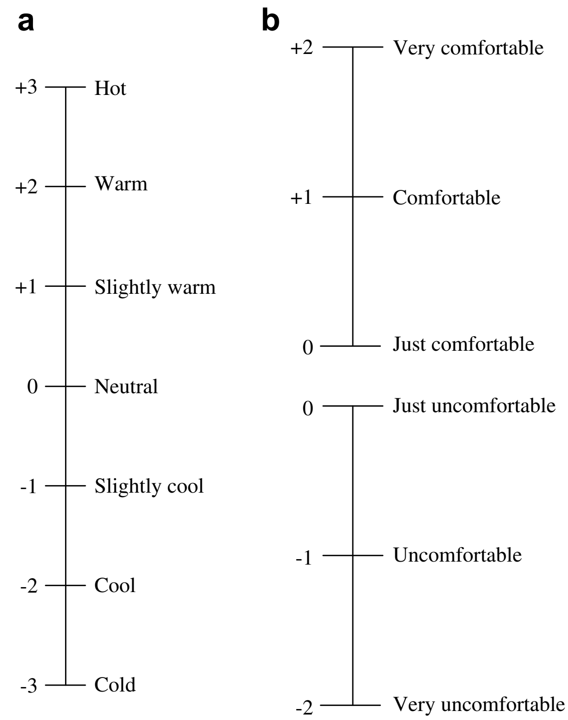

Fig. 1. Voting scales.

Subjects felt warm and slightly uncomfortable in the uniform conditions and face thermal sensation was equal to overall thermal sensation. When face cooling was supplied, face thermal sensation dropped immediately from warm to slightly cool, and overall thermal sensation dropped as well from warm to slightly warm and overall thermal comfort changed from slightly uncomfortable to slightly comfortable. After the first moment of face cooling, subjects' thermal responses changed gradually and slightly and reached almost constant at the end of exposure. In order to test whether the responses reach steady state or not, repeated measure ANOVA and paired-sample *t*-tests were performed based on the normal distribution test (Shapiro–Wilk's *W* test) of the data and it was found that the responses obtained in all conditions reached steady state within 20 min ($p>0.05$). Therefore the subjects' responses were divided into three groups: responses to steady and uniform conditions (the first two votes), responses to dynamic conditions (the 3rd vote to the 15th vote) and responses to steady and non-uniform conditions (the last three votes). It can be also

3. Results

3.1. Observations

Taking the condition of warm ambient room with cool local airflow as an example, observations on face thermal sensation, overall thermal sensation and comfort were shown in Fig. 2. The responses obtained under uniform and non-uniform conditions were collected and the mean votes of all subjects are shown in Fig. 2.

Table 1
Experimental conditions

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

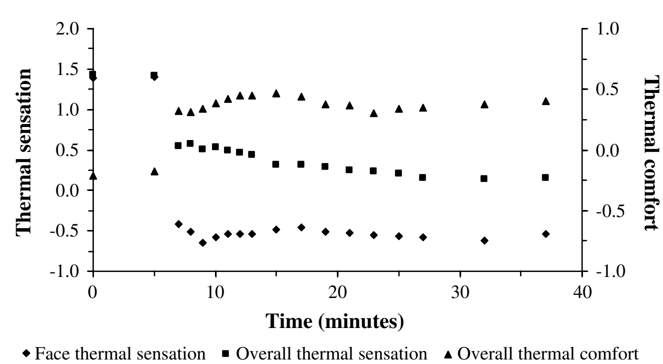

Fig. 2. Thermal responses change with time in a face cooling condition (room temperature 35 °C, target temperature 22 °C, face cooling was supplied at 7th minute).