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Predictive model of local and overall thermal sensations for non-uniform environments

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ABSTRACT

This paper proposes a quantified model for local and overall thermal sensations in non-uniform thermal environments. Human subject tests were carried out in a controlled environmental chamber. In total, 179 tests were performed on 112 participants, including 52 neutral condition tests and 127 local ventilation tests. Seven body parts (head, chest, back, arm, hand, leg and foot) were independently cooled or heated by local ventilation, while the rest of the subjects' bodies were exposed to a warm or neutral environment. Simultaneously, participants' responses for both local and overall thermal sensations were recorded. Skin temperatures were monitored by thermal resistance sensors on 14 of the local test sites. The relation between local thermal sensations and skin temperatures were analyzed using correlation statistic analysis. The principal component regression approach was adopted to eliminate the significant multicollinearity of thermal sensation among each body part. A predictive model was proposed for overall thermal sensation that integrates a local thermal sensation psychological model and an overall thermal sensation weighting factor model. The results show that local thermal sensations can be predicted by skin temperatures to a high degree of accuracy for local ventilation conditions. The weighting factors of local thermal sensation on overall thermal sensation produce integrated values, and there is little difference among the values derived from the seven body parts. Since this model is based on skin temperature, its application is not limited by environmental parameters and clothing conditions, and as a result it will be useful for designing and evaluating non-uniform thermal environments.

1. Introduction

As the Century 21st progresses, the task of decreasing the energy consumption of buildings will become increasingly urgent. New methods of air conditioning and building design, such as personal environmental control systems, floor air-supply systems and natural ventilation, are being developed to improve both indoor air quality and energy consumption. The problem is that occupants often complain of discomfort in non-uniform thermal environments employing these personal environment control systems. Predicting overall thermal sensation in non-uniform environments is complex, for it is related to local thermal sensations in different regions of the body. Quantifying thermal sensations for both local and whole body is the first step toward developing a practical predictive model. Consequently, we carried out a number of experiments on human thermal sensations to evaluate non-uniform thermal environment.

Some studies developed equivalent environmental parameters to evaluate non-uniform thermal environments. In 1989, Wyon et al. [1] proposed Equivalent Homogeneous Temperature to evaluate non-uniform environment in automobile. In 1992, Ingersoll et al. [2] predicted physiological data for head, torso and feet individually by thermoregulation simulation and then calculated Predicted Mean Vote (PMV) for three different body parts. Then he used the percentage of skin surface area of different body part to get the average PMV value for the whole body. In 1993, Matsunaga et al. [3] proposed Average Equivalent Temperature (AET) to calculate PMV in non-uniform environment. The AET is weighted by surface area of three local body parts: head, abdomen and feet. The equivalent temperature for local body part is derived from thermal manikin test. In 2003, Nilsson [4] suggested comfort zones for 16 body parts and the whole body using Equivalent Homogenous Temperature by manikin tests. Comfort zones were shown by three pistes which represented cold but comfortable, neutral and hot but comfortable individually.

Many researchers found that physiological parameters had a good correlation with thermal sensations. In 1992, de Dear et al. [5] proposed a Dynamic Thermal Stimulation model for thermo

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receptors in the skin. He used skin temperature and the rate of its change as input parameters and found that the change of thermal sensation corresponded closely with the thermo receptor impulse frequency. In 1995, Kohri et al. [6] used a two-node physiological model to calculate Standard Effective Temperature [7] for 11 body segments corresponding to the body parts of their thermal manikin in vehicle environment, and then calculated the average skin temperature and skin wettedness. In 1997, Brown and Jones [8] developed a model which calculated skin temperature and skin wettedness, and quantified thermal sensation and thermal comfort. In 1999, Fiala et al. [9] collected data from other studies, and regressed thermal sensations with physiological parameters. He found that in stable environment, there was a robust correlation between average skin temperature and thermal sensation. In 2002, Guan [10] proposed dynamic models for overall thermal sensation and local thermal sensations (head, chest, back, arm, hand, abdomen, thigh, leg, calf and feet) independently in a car environment. Body physiological data were calculated by a transient thermoregulation model, like skin temperature, heat fluxes, sweat rate, core temperature. The study revealed a close correlation between the whole body thermal sensation and local thermal sensation. The whole body thermal sensation tends to follow the cooler local body thermal sensation when the overall sensation is below neutral and trends to follow the warmer local body thermal sensations when the overall sensation is above neutral.

Some advances were made in developing the relationship between overall thermal sensation and local thermal sensation. In 1981, the research from Hildebrandt et al. [11] found that the lower the whole thermal sensation, the higher is the local thermal sensation with the same local skin temperature. In 1992, Hagino and Hara [12] studied car thermal environment and developed a weighting factor model, involving some body parts which were exposed to the air motion and the sun radiation. In 2003, Zhang [13] carried out a series of human subject tests in non-uniform environments and developed a predictive model for local and overall thermal sensation and thermal comfort in stable and transient environments, in which local and mean skin temperatures were used to evaluate local thermal sensations. 19 local body parts were cooled or heated. She derived the relative influence of body parts on overall thermal sensation and comfort as: most influential, least influential and moderately influential. She also advanced an overall thermal sensation and thermal comfort model using weighting factors of local thermal sensation. Later Zhang et al. [14] used a new method to develop the overall thermal sensation model. The model has two forms, depending on whether all of the body's segments have sensations effectively in the same direction (e.g warm or cool), or whether some segments have sensations opposite to those of the rest of the body. For each, individual body parts have different weights for warm vs. cool sensations, and strong local sensations dominated the overall thermal sensation. In 2005, Zhang and Zhao [15] carried out human subject tests under several local body part exposure conditions and proposed an impact factor method to build overall thermal sensation predictive model only using exposed local thermal sensation (head, chest and back). Simultaneously, a weighting factor model for overall thermal sensation was also derived from head, chest, back and lower body thermal sensations. In 2007, Duanmu [16] carried out personal environmental control tests in task-ambient air conditioning environments with local cooling of head, upper body and lower body. Results showed that overall thermal sensation had a positive correlation with local thermal sensations in head, upper body and lower body, with the highest correlation for the upper body, moderate correlation to that in the head and least correlation with the lower body parts.

The above research yielded qualitative or quantitative models for evaluation of thermal sensations in non-uniform thermal environments. But some of them ignored the correlation between local body part and whole body and the heat transfer between different body parts, some were applicable in the special test environment, some did not show models for both local and overall thermal sensations and some simulated physiological parameters from human body thermal regulation models of limited accuracy. Zhang [13] built a complete model based on tested skin temperatures, but the local heating tests data were limited. The air flow was conducted to a sleeve to supply local ventilation on each body part, which was not realistic in office buildings. In this paper, local ventilation supplied the air motion directly to the body part and the effect of local thermal sensation on the overall thermal sensation was studied. Parameters were established to evaluate local thermal sensation and overall thermal sensation in non-uniform environments. Finally, a model was developed to predict local thermal sensation in local ventilation systems supplying heating and cooling air motion. Also, a model predicted overall thermal sensation using statistically derived weighting factors.

2. Methods

The basic experimental protocol was to administer tests in a controlled environmental chamber and gather response data reported by the test subjects. The experiments were divided into two parts: uniform tests for getting neutral skin temperatures and non-uniform tests for deducing the models of local and overall thermal sensations.

2.1. Experimental equipments and measurement sites

Experiments were carried out in a controlled environmental chamber with a floor surface area of 7.5 m × 5.6 m and a height of 3.6 m at Dalian University of Technology. Three workstations were set up for personalized ventilation. Two workstations were located in one side of the center line of the chamber and another workstation was located in another side of the center line. They had a distance of 1.8 m from the nearest wall. The distance between two workstations was 2.8 m. The chamber's air temperature and humidity were controlled automatically, and the control accuracies were ±0.5 °C and ±5% respectively. The ventilation method in the chamber had a ceiling supply and floor return. The air velocities in the ambient area were measured near the workstations using hot wire anemometer (ZRQF-J, Bejing Test Instrument Co. Ltd., China). The test accuracy was 0.01 m/s. One test site was located at the center of the chamber with a height of 1.1 m from the floor. Four test sites were located around each workstation individually at a distance of 0.3 m from the participant and a height of 1.1 m from the floor which was for a sedentary person. The mean air velocity was 0.1 m/s, with a standard deviation of 0.02 m/s and a turbulence intensity of 21%. The ambient air velocity was perceived as still air by the participants. The velocity was also measured at a horizontal distance of 0.8 m from the floor return air intake which was 0.2 m/s (as the workstation was at a distance of 2.5 m from the return air intake, there was no effect from the return air velocity on the participant in the workstation). Ambient air temperature was measured using standard mercury thermometer (Grade II, Weigong Boli, China) and data logger (RHLOG-T-H, Tsinghua Tongfang, China). The test accuracy was within 0.1 °C and 0.5 °C respectively. Relative humidity of the chamber was collected by the same data logger. Three test sites for ambient air temperature were located at the center of the room with a height of 0.1 m, 0.6 m and 1.1 m from the floor. Another four test sites were located 1.0 m inward from each wall with a height of 1.1m. The air temperatures at different