Building and Environment 46 (2011) 2342–2350

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Thermal sensations of the whole body and head under local cooling and heating conditions during step-changes between workstation and ambient environment

Quan Jin [a,*], Lin Duanmu [a], Hui Zhang [b], Xiangli Li [a], Hongbo Xu [a]

[a] *Institute of Building Environment and Facility Engineering, Dalian University of Technology, Dalian, Liaoning 116024, PR China*
[b] *Center for the Built Environment, University of California, Berkeley 94720, USA*

ARTICLE INFO

Article history:
Received 13 February 2011
Received in revised form
29 April 2011
Accepted 18 May 2011

Keywords:
Thermal sensation
Step-change
Non-uniform
Local ventilation
Personal environment control

ABSTRACT

This paper examines people's thermal sensations during step-changes between ambient and workstation environments with a local ventilation device installed to supply-air motion around heads. We conducted human subject tests in a controlled environment chamber for summer and winter conditions. We performed 29 tests. The ambient air temperatures were 28 and 30 °C for summer conditions and 19 °C for winter conditions. The local supply-air temperatures were at 24, 28 and 30 °C for summer and 50 °C for winter. The supply-air velocities of the local ventilation device were at 3, 3.5, and 5 m/s for summer and 3.5 m/s for winter. The air temperatures near heads were 26–30 °C for summer and 32 °C for winter. The velocities along the jet-flow line at a distance of 10 cm from heads were 1.4–2.6 m/s for summer and 1.8 m/s for winter. In total, 23 subjects participated in the tests, and each subject participated in 1∼2 test conditions. Both the dynamic and stable thermal sensations of head and whole body were analyzed. When head is cooled by local ventilation, head thermal sensation has an effect on overall thermal sensation. When subjects moved from the workstation, where local devices were installed, to the ambient environment that was warmer in summer and colder in winter than the workstation, both overshooting and hysteresis were found. These thermal sensation changing trends in non-uniform step-change environments are helpful in personalizing environment control designs and exploring the possibilities of saving energy in buildings.

1. Introduction

Step-changes between two environments are common in daily life, such as walking from the indoors to the outdoors, walking from the office into the hallway and getting into and out of a car. When installing local ventilation device at a workstation (also called personal environmental control systems, PEC systems), there is another type of step-change that occurs between the workstation and the ambient environment. This paper examines changing patterns of overall and head thermal sensation during step-changes between a workstation at where a local ventilation device is installed to blow air toward occupants' heads, and the ambient environment where there is no local ventilation device installed.

There have been a number of studies to examine thermal sensation responses in the step-change process. Gagge [1] in 1967 carried out experiments that had subjects move between two uniform environments with a temperature difference of 6∼20 °C and proposed the important phenomena of thermal sensation's anticipatory and hysteresis. When the step-change is from cold to neutral or to warm, or from hot to neutral or to cold, anticipatory occurs which is probably caused by the sense of comfort that occurs before the body temperature changes. When step-change is from neutral to cold or to warm, hysteresis is especially obvious. Later, Wyon [2], Glickman [3] and Nagano [4] also found similar responses. de Dear [5] studied overall thermal sensation responses during up-step and down-step-changes when people moved between two twin chambers. Immediate sensations resulting from the temperature up-steps (from neutral to slightly warm, from slightly cool to neutral, and from neutral to neutral) showed a sharp increase, which approximately equaled the final steady-state value, while initial impressions of temperature down-steps (slightly warm to slightly cool, slightly warm to neutral, and neutral to slightly cool) overshot the final steady-state responses considerably. The author explained that the dynamic component of the thermal sensory system is capable of anticipating the steady-state response to a suddenly warmer environment. While the overshoot in sudden step-down tests appeared to result from cold thermo receptors being closer to the skin surface than heat thermo

* Corresponding author.
E-mail address: jq51yyy@gmail.com (Q. Jin).

0360-1323/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.buildenv.2011.05.017

receptors and that cold receptors are more sensitive to the skin temperature changing rate than heat receptors. In Zhang's dissertation [6], the quick overshooting appeared in the following step-changes. When face warming is applied, facial thermal sensation displayed gradual pattern and overall thermal sensation had a quick overshooting pattern. When the warm stimulation was removed, both of the two thermal sensations displayed transient overshooting. When face cooling was applied and removed suddenly, both thermal sensations showed transient overshooting. When the head (excluding the face) experienced the step-changes, the overshoot did not occur.

A number of studies have been performed on PEC to improve human thermal comfort (Melikov et al. [7], Bauman et al. [8], Brook and Parson [9], and Knudsen and Melikov [10]). The air movement enlarges the range of ambient temperatures in which people are comfortable and improves occupants' perceived air quality (Bauman et al. [8] and Arens E et al. [11]). Some studies showed that the head is an influential body part for whole body thermal comfort and local ventilation on head is effective for cooling (Taniguchi et al. [12], Zhang [13], and Arens et al. [14]). One of the physiological reason is that head is a very important body part for heat dissipation of the whole body. Zhang's dissertation [6] studied in detail the thermal comfort responses for different body parts and the whole body. She found that the local comfort of the face, feet, and hands predominate in determining a person's overall thermal comfort in warm and cool conditions. Later, she performed subjective experiments with a PEC system, which included local cooling on the head and hands by air motion and local warming on the hands and feet by conduction and radiation. The results showed that comfort is well maintained with the PEC system in the tested environmental temperatures of 18 ~ 30 °C, and the energy savings of HVAC systems can be as high as 30%. Zhang Y [15] examined the effects of local exposures of the face, chest, and back on overall thermal sensation, comfort, and acceptability. When the face is cooled by local ventilation, overall thermal sensation changed significantly. The author explained the physiological reason is that the head, which has the area perfused by a rich superficial vascular supply, acts as a radiator. When face cooling is provided, it improved thermal acceptability more than other body parts and the boundary of the acceptable range of room temperature can shift from 26 to 30.5 °C with less than 20% dissatisfaction. It provides evidence that there is a reasonable increase for the ambient temperature when using local ventilation to cool the face.

From the results summarized above, three things are clear. First, local ventilation on the face could improve thermal comfort and enlarge the ambient temperature range for comfort, so energy consumption will be reduced. Second, the face is an influential body part when applying local ventilation, which can produce considerable change on overall thermal sensation. Third, thermal sensation appears as overshooting and hysteresis during step-changes. However, there was no step-change test done between the ambient environment and the workstation, to explain how people feel when they step outside their workstations with PEC systems into the ambient that does not have a PEC system. In Zhang's study [6], there was a sudden stimulus on a local body part, such as head, hand and feet, which appears to be similar to the step-change from the ambient to the workstation. However, when the stimulus is removed, it is not similar to the step-change from a workstation into an ambient environment, because the environment change is gradual in Zhang's study, which is different from the sudden change from a workstation to the ambient environment, so the signals received by the thermal receptors are different. Also, the supply-air temperature in Zhang's tests was low, which is not realistic in office environments and does not use energy efficiently. The purpose of this study is to test human responses during a step-change between ambient environment and a workstation with a small temperature difference between the air from the local supply nozzle and the ambient environment.

We should note that different terms are used in literature to express the two types of thermal sensation responses after step-changes, anticipatory or overshooting and hysteresis or gradual pattern. In this paper, we use overshooting and hysteresis to describe the phenomena, which refer to what occurs after step-changes, in which the initial thermal sensation reaches the peak value immediately and gradually, respectively.

2. Methods

2.1. Experimental equipment and test conditions

The experiments were carried out in a controlled environment chamber at Dalian University of Technology. The chamber's air temperature and humidity were controlled automatically, and the accuracy controls were ±0.5 °C and ±5%. There were two areas, which were the workstation environment and the ambient environment (see Fig. 1a and b). In the workstation, pictures and books were added to create an office atmosphere. The ventilation method in the chamber had a ceiling supply and floor return. The air supplied to the chamber ambient is mixed of fresh air and recirculated air. The air velocity in the ambient area is less than

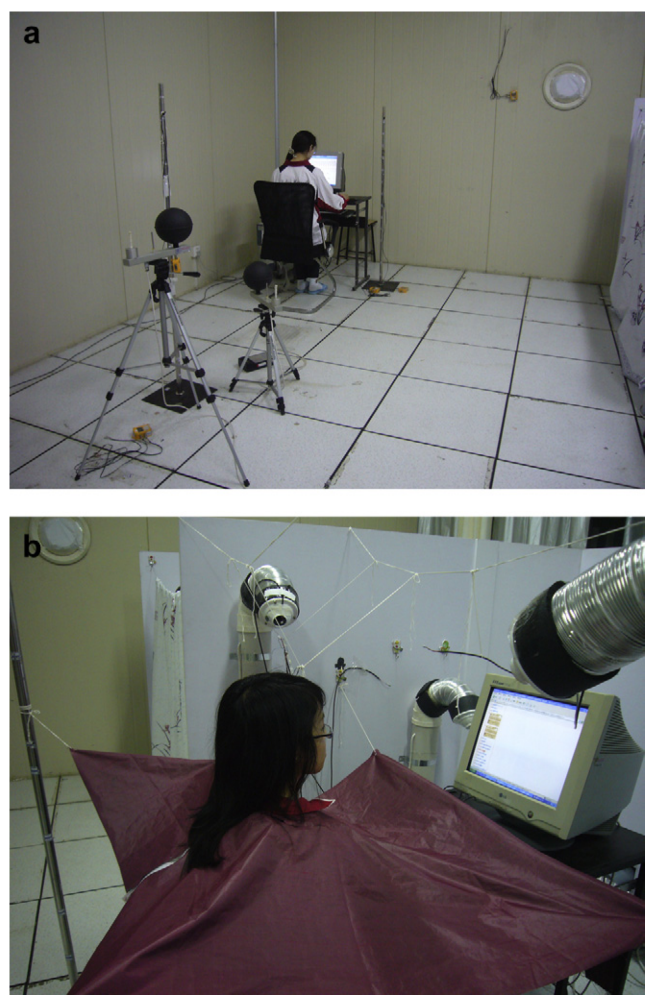

Fig. 1. Experimental facilities a) Ambient environment b) Head local ventilation and fabric devices.