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Human skin temperature and thermal responses in asymmetrical cold radiation environments

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ABSTRACT

Many previous studies on human thermal and physiological sensation were done in the box-like chambers which are different from the real environments. The subjects wore summer clothing in the earlier studies which was different from Chinese northern people's clothing in winter.

In order to investigate the effect of cold radiation from the outer window on human skin temperature and thermal responses in Harbin winter, a study was carried out in a climate chamber with asymmetrical radiation environments. 20 subjects worn winter clothes participated in the experiments in a chamber with an exterior window which is a more realistic environment in practice.

The environmental parameters and skin temperatures were recorded. Meanwhile, the subjects were asked to fill in the questionnaires on five local and overall thermal sensation and thermal comfort.

The results show that the cold radiation from the outer window might result in the decreases of local skin temperatures, especially for calf and back. The mean skin temperature is 33.0 °C when subjects felt thermally neutral for the whole body. The results appeared that asymmetrical radiation from the exterior window and clothing has no influence on the preferred mean skin temperature. Overall thermal sensation and mean skin temperature showed a good linear relationship, which showed that human overall thermal sensations may be predicted by their mean skin temperatures. Mean skin temperatures would have less influence on local thermal sensation when local skin temperature was higher than that in neutral condition.

1. Introduction

Harbin is located in the northeast of China. During the day, the outside average temperature is about −10 °C in Harbin winter. The internal surface temperatures of outer window are much lower than the indoor air temperature in winter. Residents usually feel cold when they seat nearby outer windows. The terminal heating equipments, such as radiators are often used to maintain the appropriate indoor temperatures. Therefore, the indoor thermal environment is asymmetrical. In an asymmetrical radiation environment, the local thermal sensation and thermal comfort is different.

Olesen pointed out that thermal neutrality for the body as a whole is insufficient in itself to ensure thermal comfort. Warm or cold discomfort of the feet can occur when man exposed to asymmetric radiant climate from floor [1]. Therefore, it is important to study the local and whole thermal sensation and comfort and their relationship in an asymmetrical radiation environment.

McNall examined the thermal and comfort sensations of sedentary persons exposed to asymmetric radiant fields in 1970 [2]. 8 or 10 subjects took part in each experiment in a chamber with one cooled or heated surface of walls surrounded, or with a cooled or heated ceiling. The results indicated that the subjects of the hot wall series had a significantly lower probability of feeling "comfortable" than those of the other series. The thermally neutral zone was applicable for the cool wall series, not for the hot wall series.

Fanger provided the limits of overhead radiation, in which people in thermal neutrality did not feel discomfort based on 16 subjects' results in a chamber study [3]. Fanger et al. analyzed the comfort limits for asymmetric thermal radiation [4]. 36 or 16 subjects attended each test. The results indicated that radiant asymmetry at a warm wall made less discomfort than a cool wall. A cool ceiling made less discomfort than a warm ceiling.

Sakoi investigated the thermal comfort, skin temperature distribution, and sensible heat loss distribution of the 36 sedentary

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persons in asymmetric radiant fields [5]. The results indicated that the mean skin temperature and mean sensible heat loss were inadequate for describing the overall comfort sensation; other parallel variables such as the distributions of skin temperature and sensible heat loss were necessary.

Kitagawa detected the local and overall thermal comfort under a radiant cooling system [6]. They carried out 3 conditions and 4–11 subjects took part in each condition. The results showed the most comfortable sensation vote was attained in the condition where thermal sensation vote was not neutral but slightly cool with the vote of −0.5.

Schellen et al. investigated gender differences in thermophysiology and thermal comfort in non-uniform environmental conditions [7]. 20 healthy subjects were exposed to two different experimental conditions: a convective cooling situation and a radiant cooling situation. The results showed that under both experimental conditions the actual mean thermal sensation votes significantly differed from the PMV-index; the subjects felt colder than predicted.

The above radiant asymmetry caused by a cool or hot wall, or a cool or hot ceiling. And the studies were done in the box-like chambers which are different from the real environments. And the analyses were focused on the subjects in thermal neutrality states in generally. However, people stay in a real environment with an outer window, which may cause more cold radiation and people may in the states far away from thermal neutrality. Additionally, the subjects wore summer clothing in the previous studies, and the clothing insulation was small, which was different from Chinese northern people's clothing in winter.

In this project, we have gone a step further in separating the local thermal sensation and comfort due to the window cold radiation from general cool or neutral sensation conditions for the body as a whole. 20 subjects worn winter clothes participated in three experiments in a chamber in Harbin winter.

2. Methods

2.1. Study design

The experiment was conducted in an artificial chamber, which is consisted of room A and room B. The air temperature of room B can be controlled in the range of −20–0 °C, which is used to simulate the outdoor climate in severe cold area in China. The wall and window between room A and room B can be treated as the exterior wall and window of room A. The room A is 3.9 m by 3.3 m in plan and a 3.0 m ceiling height was employed. An electrical heater was placed in the opposite of the window in the room A to keep the indoor air temperature at about 18–24 °C, which is a more realistic environment in office or residential buildings.

Three experimental conditions were slightly cool, neutral conditions with asymmetrical cold radiation, and a neutral uniform condition, with the mean indoor air temperature of 19 °C, 22 °C and 20 °C, respectively. The experimental contents were blind to all subjects across the experiment.

2.2. Subject characteristics

In the climatic chamber studies on thermal sensation and comfort, the number of subjects chosen was no more than 20 in generally, such as Refs. [2–4,6,7]. In recent years, some chamber studies have been carried out around the world. Wyon et al. studied the limit for human exposure to low winter humidity indoors. 30 subjects were exposed for five hours in each environmental condition in a climate chamber [8]. Tochihara et al. researched the age-related differences in cutaneous warm sensation thresholds of human males based on 12–13 subjects [9]. Yasuoka et al. studied the differences in thermal responses to skin cooling. 13 women took part in the experiment [10]. Chen et al. analyzed temperature steps on 16 subjects' skin physiology and thermal sensation response [11]. Wang et al. studied 20 subjects' thermal sensation under hypobaric conditions [12]. Jin et al. studied 23 subjects' thermal sensations of the whole body and head under local cooling and heating conditions [13]. Chow et al. studied thermal sensation of Hong Kong people in air-conditioned environment [14]. Wang et al. analyzed the effect of cold radiation on 20 subjects' thermal sensation and comfort under dynamic thermal conditions [15]. The number of subjects was about 20, except the studies in Refs. [5,8,14].

20 healthy college-student volunteers (10 males and 10 females) participated in the study. The subjects had lived in Harbin more than two years and had fitted to the Harbin cold climate. A male and a female subject attended an experiment at the same time, and the distance between the subjects and the outer window was 1.0 m.

According to the results of thermal comfort field survey in Harbin, the clothing insulation for the residents is 0.88–1.37 clo [16–18], and the mean value is about 1.0 clo. The subjects were asked to wear the similar clothes with the clothing insulation of 1.02 (long underwear top, long underwear bottoms, thin long sleeve sweater, jeans, shoes and ankle-length athletic socks, including the chair insulation).

The height and weight of the subjects were measured by a weighing scale. The background characteristics of the 20 subjects are summarized in Table 1.

Table 1
Background characteristics of subjects (mean ± standard deviation).

Gender	Age	Height (cm)	Weight (kg)
Female	21.3 ± 0.47	159.1 ± 4.6	54.2 ± 5.1
Male	21.3 ± 0.94	171.8 ± 6.4	60.5 ± 5.9
Total	21.3 ± 0.75	164.3 ± 7.6	58.7 ± 7.1

2.3. Measurement parameters

The measured environmental parameters are air temperature, relative humidity, air velocity, black ball temperature and surface temperatures of the chamber. The measurement equipments and their resolutions are described in Table 2. During the experiment, the air temperature, black ball radiation temperature and relative humidity were recorded every 5 min, while the air velocity was measured every 15 min.

According to ISO 7726 standard [19], the measurement points of room A are shown in Fig. 1. The measurement point 1 was placed in the center of the room A. The air temperature in room A was measured at 0.1 m, 0.6 m, 1.1 m heights, which represented the ankle, waist and head of a seated subject, respectively. And the black ball temperature, air velocity, relative humidity were measured at 0.6 m height. The measurement point 2 was placed nearby the subjects. Its air temperature was measured at 0.1 m and 1.1 m heights.

The surface temperatures of the exterior window were more focused on than those of the other surfaces when measurement points were placed. 6 measurement points were placed uniformly on outer window and 2 measurement points were placed on the outer wall, seen in Fig. 1. 1 measurement point was placed in center of the other inner surfaces, respectively.

The skin temperature was measured by the copper–constantan thermocouple, collected and recorded by BEC-Ca multichannel data acquisition instrument. The measurement error of the thermocouple