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Human thermal physiological and psychological responses under different heating environments

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ABSTRACT

Anecdotal evidence suggests that many residents of severely cold areas of China who use floor heating (FH) systems feel warmer but drier compared to those using radiant heating (RH) systems. However, this phenomenon has not been verified experimentally. In order to validate the empirical hypothesis, and research the differences of human physiological and psychological responses in these two asymmetrical heating environments, an experiment was designed to mimic FH and RH systems. The subjects participating in the experiment were volunteer college-students. During the experiment, the indoor air temperature, air speed, relative humidity, globe temperature, and inner surface temperatures were measured, and subjects' heart rate, blood pressure and skin temperatures were recorded. The subjects were required to fill in questionnaires about their thermal responses during testing. The results showed that the subjects' skin temperatures, heart rate and blood pressure were significantly affected by the type of heating environment. Ankle temperature had greatest impact on overall thermal comfort relative to other body parts, and a slightly cool FH condition was the most pleasurable environment for sedentary subjects. The overall thermal sensation, comfort and acceptability of FH were higher than that of RH. However, the subjects of FH felt drier than that of RH, although the relative humidity in FH environments was higher than that of the RH environment. In future environmental design, the thermal comfort of the ankles should be scrutinized, and a FH cool condition is recommended as the most comfortable thermal environment for office workers. Consequently, large amounts of heating energy could be saved in this area in the winter. The results of this study may lead to more efficient energy use for office or home heating systems.

1. Introduction

The area of Harbin, China experiences mean outdoor temperatures of $-10\,°C$ in the winter. The inhabitants rely primarily on one of two types of indoor heating systems: radiator or floor heating systems. These systems create non-uniform heating of indoor spaces leading to marked differences in the physiological and psychological thermoregulatory responses. Skin temperature, heart rate, blood pressure, and thermal sensation are reported to vary considerably depending on which type of heating system is utilized in the winter.

Some previous empirical researches on human thermal responses in asymmetrical heating environments are represented as follows. Nevins et al. (1964) found that thermal comfort of the feet shifted from a comfortable state to a hot state as floor temperature increased. But the overall thermal sensation shifted surprisingly from slightly cool state towards a comfortable state. Olesen et al. (1980) pointed out that when room temperature was maintained at thermal neutrality ($PMV=0$) for a sedentary person, local thermal discomfort would be minimal, and the thermal conditions would be acceptable in the entire occupied zone. Huizenga et al. (2004) studied the human thermal responses to partial and whole body heating or cooling. They found that skin temperatures of hands and fingers fluctuated significantly when the thermal neutral state of whole body was nearly achieved. The core temperature increased in response to skin cooling, and vice versa. Zhang et al. (2003, 2010a,b,c) reported that individuals could easily perceive coolness on hands and feet and the overall thermal discomfort was in accordance with these local sites in cool environments. However, in warm environments, the overall thermal discomfort was closely related with discomfort of the head. A "complaint-driven model" was derived from those findings.

The above studies were generally based on a heating or cooling environment separately, instead of an asymmetric environment with impacts from both heating and cooling sources. Furthermore,

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the subject's clothing insulation was lower in the mentioned studies, which doesn't comply with the local dressing habits in the severe cold area of China during the winter. Previous field surveys found that the local occupants tended to feel warmer and more comfortable in a floor heating (FH) environment than in a radiant heat (RH) environment. Do people really perceive more comfort in a FH environment? Can they achieve an acceptable thermal state in a cool environment with a FH system? In addition, most of occupants in FH environments often complain about dryness. However, all these claimed phenomena have not been empirically verified. Therefore, an experiment was conducted in a controlled climate chamber to address these questions and provide some explanations. Furthermore, practical implications are proposed for the future design of office or home heating systems.

2. Experimental method

2.1. Climate chamber and equipment

The experiment was carried out in a climate chamber in Harbin; the dimensions of the chamber are illustrated in Fig. 1. There were two rooms in the chamber (Room A and Room B). The indoor environment could be simulated in room A and the outdoor climate could be simulated in room B. The walls of the chamber were constructed by the polystyrene foam board and covered with the color steel plate with a total thickness of 150 mm. The heat transfer coefficient of the wall was 0.404 W/ (m^2 K), which represented real building walls in severely cold areas of China. The electrical heating cables were placed under the floor, controlled by a thermostat. And a radiator with hot water inside was heated by a controllable electric boiler outside the chamber. The air temperature in Room B was controlled by a chiller with a control range was from −20 to −5 °C and a precision of ±0.5 °C.

The air temperature, inner envelope surface temperature, globe temperature, relative humidity and air speed were measured in the experiment.

The subjects' skin temperature and inner surface temperature of chamber was measured by using T copper–constantan thermocouples linked to a multi-channel data logger. These temperatures were monitored and recorded at an interval of 5 min by a computer outside the chamber. Prior to the measurement, all the thermocouples were calibrated by a standard mercury thermometer with a precision of ±0.1 °C in a thermostatic water bath. The air speed and relative humidity in room A was respectively recorded by a hot-wire anemometer and a thermohygrometer. The subjects' heart rate and blood pressure were recorded by ORMON HEM-7112 digital monitors.

The mean radiant temperature (MRT) was calculated based on the globe temperature, expressed in Eq. (1).

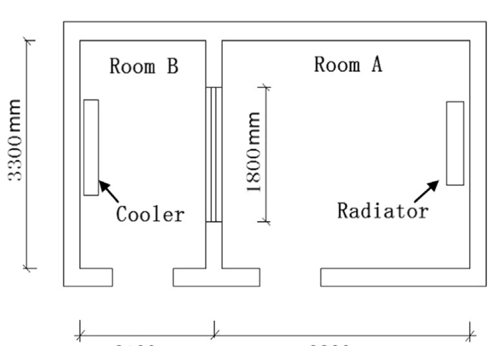

Fig. 1. Dimensions of climate chamber.

$$t_r = \left[\left(t_g + 273\right)^4 + 2.5 \times 10^8 \times v^{0.6}(t_g - t_a)\right]^{1/4} - 273 \quad (1)$$

where t_r represents the mean radiant temperature (MRT), °C. t_g represents the globe temperature, °C. t_a represents the air temperature, °C. v represents the air speed, m/s.

The specific range and accuracy of experimental equipments are shown in Table 1.

2.2. Condition design

In winter, the occupants typically inhabit rooms with an air temperature range of 19–22 °C in Harbin, based on the previous field studies (Wang et al., 2003; Wang, 2006; Wang et al., 2011). If the indoor air temperature was maintained at a comfortable but low level, a great amount of space heating energy would be saved in this area (Wang et al., 2014).

In a pilot study, the subjects respectively felt "slightly cool" and "neutral" in 19 °C and 22 °C. Therefore, 19 °C and 22 °C were termed as "slightly cool" and "thermoneutral" conditions, which were used as the ambient temperatures in the experiments.

The air temperature in room A was maintained at 19 °C or 22 °C condition during the test. In each condition, the subjects were accordingly exposed to a RH or FH environment. The air temperature in room B was maintained at −15 °C which was in accordance with the outside mean air temperature in winter in Harbin.

Atmaca and Yigit (2006) studied the effect of relative humidity on skin temperature and skin wetness under different operative temperatures. They indicated that relative humidity was not an effective parameter on the skin temperature and skin wetness if the operative temperature was maintained within an acceptable range of human thermal comfort.

In the pilot study, the relative humidity ranged from 25–40% while the air speed ranged from 0.08–0.11 m/s, which met the thermal comfort standard. Therefore, the relative humidity and air speed were not considered as influential factors on human skin temperatures in the experiments. Relative humidity and air speed were not controlled in the experiments because indoor air temperature is the only variable regulated with space heaters in Harbin. The definitions of environmental conditions are shown in Table 2.

2.3. Measure points and subjects

In China, the office space is small in most cases and office staffs prefer sitting near exterior windows to have a good view or be able to access natural daylight. Therefore, they are often exposed to a cold radiation environment in winter. In order to consider the cold radiation effect, the distance between subjects and exterior windows was set 1.0 m in the chamber.

The measure points' arrangement is illustrated in Fig. 2. The measure points' arrangement accords with ISO. 7726-2001 (2001).

The globe temperature, air speed and relative humidity were measured at the height of 0.6 m. The inner surface temperatures were measured by attaching thermocouples on the walls, windows, roof and floor.

Thirty six healthy college students were selected as volunteer subjects, 20 students in RH and 16 students in FH respectively. All the selected students had been living in Harbin for more than 2 years, and had fully acclimatized to the local climate. The gender ratio was 1:1 in each group. The subjects' height and weight were measured by an electronic scale. The characteristic data of subjects are presented in Table 3.

Type-T thermocouples were attached to the subjects' skin to measure skin temperature. The forehead, back, hand, arm and