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Thermal comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel)

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ABSTRACT

This study aims to investigate subjective comfort and energy consumption in cold environment with retrofitted Huotong (warm-barrel). A series of experiments was conducted in one experimental room in Hunan University, China in winter. 16 subjects were exposed to the environments at 9, 12, 15 and 18 °C with retrofitted Huotong. During each test, subjective responses and Huotong's energy consumption were recorded. The obtained results indicates that Huotong maintained overall and local comfort in cold environment. With it, 90% acceptable temperature range could be extended to 9 °C. Thermal sensation, comfort and acceptability improved within 15 min after subjects turning on Huotong, while their preference for warm environment was weaken. Moreover, the heating power required for maintaining comfort increased as temperature was lower. When air temperature dropped from 18 to 9 °C, the average heating power rose from 50.3 to 165.6 W for each person. In addition, based on Corrective Power (CP), a new index (Corrective Energy & Power, i.e. CEP) for evaluating performance of both comfort and energy consumption of personal comfort system (PCS) was proposed. This index makes it possible to compare different PCSs in terms of extending acceptable temperature range and energy-efficiency simultaneously.

1. Introduction

Indoor environment is important for people's health. In modern buildings, large amount of energy is consumed by air conditioning systems to create comfortable environment, while there are still discomfort complaints [1]. Personal comfort system (PCS), a concept which refers to systems or devices that change person's local thermal condition (one or several body parts), was proposed by Zhang et al. [2]. PCS meets the demand of personal adjustment thus improving users' comfort. Also, it helps save energy by extending comfortable temperature range. Specially, PCS has exerted great potential for maintaining people's comfort in outdoor environment with cold climate [3]. Personal heating system is one important part of PCS. By heating some body parts through radiation, conduction or convection, personal heating system can eliminate local discomfort of occupants in cold environment. Therefore, occupants could keep comfortable at lower temperature. This would also contribute to extending setting temperature range of air conditioning system, thus achieving energy-saving. In recent years, personal heating system has drawn much attention from researchers.

Watanabe et al. [4] carried out a series of experiments to examine the performance of an individually controlled system which comprised convection-heated chair, under-desk radiant heating panel and floor radiant heating panel. The obtained results showed that heating chair, under-desk heating panel, and floor heating panel produced effects of temperature increase of 5.2, 2.8, and 2.1 °C respectively when indoor temperature was 20 °C. Zhang et al. [5] conducted a field investigation on the influences of foot-warmers on comfort and energy saving in office rooms. The obtained results indicates that using foot-warmers helped lower the indoor setting temperature in winter (from 21.1 to 18.9 °C), thus significantly reducing energy consumption of air conditioning system. Zhang et al. [6] established two workstations which were equipped with heated keyboards and foot-warmers. Those workstations maintained neutral thermal sensation and improved acceptance of subjects at 18 °C, while the heating power was merely 59 W. Deng et al. [7] carried out a series of experiments on a kind of heating chair which used thermoelectric materials. Based on the results of subjective responses from 36 participants, they reported personalized heating provided warmer sensation and better comfort in cool environment (16 °C). Similarly, Pasut et al. [8]

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conducted experiments on another type of heated chair. They demonstrated that heating buttocks through direct conduction improved subjective comfort when ambient temperature was 16 °C. Then they undertook another study where the chair heated the back and buttocks at the same time, and obtained similar results [9]. Zhang et al. [10] pointed out that if supply temperature of heated chair could be well controlled, 90% acceptable temperature range could be extended to 15.6 °C. Yet this conclusion was not validated by experiments. Further, Enomoto et al. [11] found that people could maintain neutral sensation when indoor temperature dropped to 14°C when their lower body parts were heated by supplying hot air.

However, when it comes to colder environment, it seems that not all personal heating systems or devices would always work. In the study of Brooks and Parson [12], subjects kept neutral sensation at 10 °C but cool at 5 °C with heated seat. In the study of Oi et al. [13], people felt cool at 10 °C although they used heated seat and foot-warmer at the same time. He et al. [3] conducted a field survey on thermal comfort of sellers who were using a kind of traditional personal heating device (Huotong) in marketplaces. They reported that the acceptable temperature range of 90% acceptable could be extended to about 9 °C when Huotong was used. Wang et al. [14] designed a new kind of heating clothing with phase change material. They claimed that this garment could be used at −15 °C and save 30% energy through control process. However, this result was not validated by human experiment. Choi et al. [15] tried to explore the effectiveness of clothing incorporated with phase change material in pretty cold environment (5 °C, 65% RH). But it seems that the subjects still feel cold whether using the clothing or not. In contrast, the study of Song et al. [16] presented more positive results. Song et al. [16] tested the effects of two types of heated clothing (i.e., electrically and chemically heated clothing) on students in cold-humid environment (8 °C, 80% RH). They found whole thermal sensation of subjects was kept at neutral level when using heated clothing. Wang et al. [17] reviewed several typical kinds of personal heating garments around the world. It was confirmed that personal heating garment widened comfortable temperature range in cold environment. They also pointed out that current heating devices were faced with many problems like insufficient heating power and limitation on human activity. The case study of Verhaart et al. [18] demonstrated that 34% of HVAC energy consumption could be saved by applying PCS during the winter period, whilst improving the rate of occupant satisfaction. Zhang et al. [2] summarized a large number of studies on PCS and proposed a new indicator, i.e. corrective power (CP). CP can be used to quantify the extent to which one certain type of PCS could deviate from neutral condition while subjects still feel comfortable. This indicator also helps compare the effects of different PCSs on maintaining people's comfort in non-neutral environment.

According to the review of precious studies, it's clear that personal heating system exerted great potential for both improving peoples' comfort and saving energy. However, some problems remains unsolved. For example, most of previous researches mainly focused on the effect of personal heating system on physiological responses and subjective comfort, while ignoring their energy consumption. Energy consumption is another important factor for wide adoption of one certain type of PCS. Besides, few previous researches were conducted in extreme environment with practical heating device. Many devices or systems were tested within or close to comfort zone suggested by ASHRAE Standard 55 [19]. Some heating devices well maintained people's comfort in extreme environment, but there are ergonomic problems (like movement restriction) [16,17] because they were not commercial products or widely used. Thus, more researches of applying practical personal heating system in cold environment are quite in need.

This paper aims to investigate thermal comfort and energy consumption in cold environment with retrofitted Huotong. Huotong, a kind of traditional personal heating device with hundreds of years' history, could maintained people's comfort even when temperature was lower than 10 °C [3]. In our previous field study [3], it was found that running cost of Huotong was low. But the quantified energy consumption was not confirmed. In this study, the traditional Huotong was retrofitted. Then a series of experiments was conducted in one experimental room from January to February in 2016. During the experiments, subjects' responses were recorded as well as the energy consumption of Huotong. The results of thermal comfort and energy consumption with retrofitted Huotong at 9, 12, 15 and 18 °C were presented. Meanwhile, based on corrective power [2], a new index (CEP, i.e. Corrective Energy & Power) for evaluating the effectiveness of both comfort and energy of PCS was proposed. This new index could be helpful for comparing and applying different types of PCS.

2. Method

2.1. Experimental facilities

The experiments were carried out in one experimental room (3.8 m × 2.7 m) in Hunan University, Changsha, China. This room was used as normal office room at ordinary times, thus experimental condition could be close to real office environment. There was one window (1.5 m × 1.8 m) on the north wall but it was well shaded by thermal insulation layer (about 40 mm) and thick window curtain during the experiments. One ventilation device was installed near the window to supply fresh air at low speed. The indoor layout of experimental room was shown in Fig. 1.

Huotong, a kind of traditional personal heating device (consuming charcoal), is widely used in the rural regions in the west of Hunan Province, south of China [3]. It can be regarded as a special type of heated chair. What distinguishes it from normal heated chair or other heating devices is the complex heat transfer process, which combines conduction, convection and radiation [3]. Huotong is effective to protect occupants from cold climate in winter while the running cost was pretty low. Particularly, it's convenient for mobile vendors. Detailed information of Huotong is presented in our previous work [3]. In this study, the traditional Huotong was retrofitted. As shown in Fig. 2, an electric heater with halogen heating tube was put inside the Huotong instead of charcoal, so that it's available to measure the heating power. The heater was equipped with a stepless-adjust knob for subjects to adjust its heating power (0–1000W). This heater can be easily bought in stores or online in China. Rubber insulation layer (20 mm) was

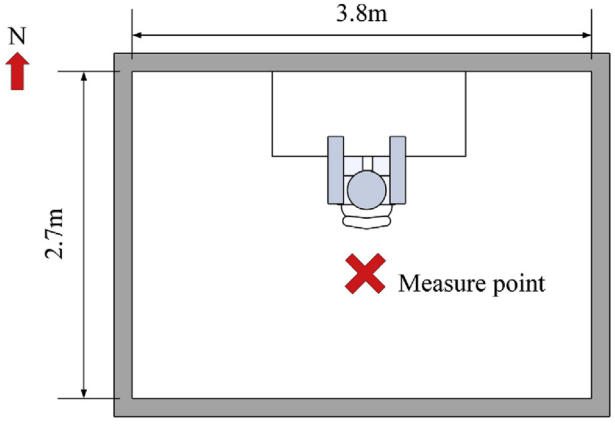

Fig. 1. Layout of experimental room.