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Hybrid cooling clothing to improve thermal comfort of office workers in a hot indoor environment

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ABSTRACT

The study aimed to examine the effect of a hybrid personal cooling garment (PCG) on improvement of thermal comfort of office workers in a hot indoor environment. Eleven male subjects underwent two 90-min trials with one in PCG (i.e., with the hybrid personal cooling garment) and another with no cooling (i.e., CON). The trials were performed in a climate chamber with an air temperature of 34.0 ± 0.5 °C, relative humidity of 65 ± 5% and an air velocity of 0.15 ± 0.05 m/s. It was found that the hybrid PCG could remarkably improve the whole-body thermal sensations (TSs), skin wetness sensations (WSs) and comfort sensations (CSs) during most of time of the trials compared with CON (i.e., from the 10th min to the 40th min and from the 70th min to the 80th min for TSs, from the 10th min and the 20th min to the end of the test for WSs and CSs, respectively) ($p < 0.05$). The upper-body and lower-body TSs, WSs and CSs were all significantly improved in PCG from the 10th min to the end of the test ($p < 0.05$). In addition, mean skin temperatures and the total sweat production were also significantly reduced in PCG ($p < 0.05$). In summary, the hybrid PCG was highly anticipated to improve thermal comfort of office workers while doing office work in the studied hot and moderate humid indoor environment.

1. Introduction

Office workers generally spend more than 90% of their time indoors [1]. Indoor thermal environments (e.g., the air temperature, relative humidity, air velocity, radiation) [2] together with the air quality and illumination significantly affect the performance and health of office workers in indoor environments [3,4]. In recent years, indoor thermal conditions have been worsened due to global warming and frequently emergent and intensified heat waves [5]. This tends to consume more energy to provide acceptable thermal conditions for office workers [5]. Thus, a great deal of attention has been paid to improve indoor thermal comfort of office workers without significant compromise of energy consumption [6].

Theoretically, indoor human thermal comfort can be improved by either adjusting the environmental condition through the Heating Ventilation and Air Conditioning (HVAC) system [6], or using personal comfort systems (PCSs) [7]. Adjusting the HVAC system to maintain the indoor environment in a standard defined comfort limit range does not always lead to a high level of comfort [8,9]. On the contrary, numerous anecdotal experiences of the overcooled buildings caused by the modern HVAC system have reflected the inflexibility of the system [9]. Furthermore, HVACs are most likely to bring about tremendous energy cost as well as environmental pollutions [6]. Considering the above problems and the widely accepted fact that great individual differences exist between genders and different age groups [10], using PCSs has been regarded as the most effective and flexible approach to fulfil individual thermal comfort needs [11]. For instance, electric fans directing at the whole body (such as ceiling fans and opposing air jets) or local body parts (such as front desk fans and fans incorporated into chairs) were widely examined by researchers on their effectiveness in improving human thermal comfort in hot indoors [12–18]. PCSs were proved to be effective in maintaining human thermal comfort in warm indoor environments without HVAC (e.g., $T_{air} < 32.0$ °C) [12,16]. However, it seems difficult to keep the human body in thermal neutral state using PCSs in hot indoors where the

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Nomenclature

HVAC	Heating, Ventilation and Air Conditioning
PCS	Personal comfort systems
PCG	Phase change garment
CON	No cooling condition
PCM	Phase change material
LCG	Liquid cooling garment
ACG	Air cooling garment
HR	Heart rate
T_c	Core temperature
$\overline{T_{sk}}$	Mean skin temperature
T_b	Mean body temperature
ΔS	Body heat storage
TS	Thermal sensation
CS	Comfort sensation
WS	Wetness sensation

air temperature is higher than 34.0 °C [12,16] and particularly in hot humid indoor environments [12,14,18]. Moreover, using PCSs may induce body discomfort (due to drought) [17,18], and bring such ergonomic problems as high noise, more energy cost and space occupation [17]. In addition, PCSs such as electric fans were not portable and could not be able to provide sustained thermal comfort.

Many researchers have discovered that human indoor thermal comfort could be improved by self-adjusting clothing [19–21]. Unfortunately, this is not always feasible for office workers because they have to wear vocational clothing even in hot summer due to social etiquette requirements. Moreover, self-adjustment of clothing had a limited benefit in improving human indoor thermal comfort, particularly in extreme harsh indoor environments [20] combined with high/low air velocities and humidity [21]. In order to solve above issues, personal cooling and heating clothing systems have been developed. Compared to the conventional clothing adjustment method, personal heating/cooling systems have shown evident ability in improving individual thermal comfort [22].

Currently, the effectiveness of personal cooling garments (PCGs) in alleviating body heat strain while exercising in hot environments has been widely examined [23–25]. PCGs have already been applied to such special fields as military training, firefighting, medical operations and sports. In general, PCGs may be divided into four categories based on the types of cooling sources, i.e., liquid cooling garments (LCGs) [26], air cooling garments (ACGs) [26–28], garments incorporated with phase change materials (PCMs) [28] and hybrid cooling garments that combine two or more of the aforementioned cooling techniques [29,30]. Literature review studies demonstrated that LCGs and cold-air ACGs could provide greater cooling benefits compared to other types of PCGs [22,23]. Nevertheless, LCGs and cold-air ACGs have many obvious drawbacks of high cost, complexity and non-portability due to the refrigeration systems connected, thus restricting them to a small range of application [23]. In contrast, PCGs incorporated with PCMs, ACGs using ventilation fans and the hybrid cooling garments combining the PCMs and ventilation fans are relatively cheap and portable, and thus they have a great potential to be applied to various work settings including indoor office work [24,25,30].

Few studies have attempted to examine the effect of PCGs in improving human thermal comfort indoors [31–34]. Several studies explored on the effectiveness of PCM cooling clothing in improving thermal comfort of special personnel such as surgeons [32,33]. Two studies were retrieved for investigating the performance of PCM cooling clothing in improving thermal comfort of office workers [31,34]. Nishihara et al. [31] examined the effects of a commercial ice vest and a PCM cooling garment in improving thermal comfort of office workers in a warm and dry environment. Gao et al. [34] examined the effect of a PCM cooling vest on an already overheated body while conducting office work in a hot environment. Results illustrated that PCM cooling vests had significant effects on local body regions rather than the whole body [31,34]. In view of ongoing research, more studies should be conducted to find out better PCGs to improve the thermal comfort of office workers in hot indoor environments, e.g., during severe heat wave incidents.

More recently, a hybrid PCG (clothing incorporated with air ventilation fans and PCMs) was developed to give full consideration of the cooling effect and ergonomic design. Thermal manikin studies have evidently showed that the hybrid PCG presented larger and prolonged cooling effect compared to single cooling methods [30]. It is of great interest to examine the hybrid PCG on its effectiveness in improving thermal comfort of office workers in hot indoor environments where the HVAC system is not available. It was hypothesized that the hybrid PCG could greatly improve both physiological and perceptual responses of office workers in the studied hot indoor environment.

2. Methodology

2.1. Human subjects

Eleven young male office workers (age: 21.9 ± 2.38 years, weight: 61.41 ± 2.54 kg, height: 1.74 ± 0.02 m, body surface area: 1.74 ± 0.04 m^2, body mass index: 20.46 ± 0.84 kg/m^2) volunteered for this study. They were physically healthy and had no history of heat illnesses, cardiovascular, metabolic or respiratory diseases. Prior to participation, all subjects were fully explained of the purpose, details and potential medical risks associated with this study. They were then asked to sign a written informed consent. They were also notified that they could quit this study at any time without penalty. This study was approved by the Ethics Committee of Soochow University.

2.2. Hybrid personal cooling garment (PCG)

A set of hybrid PCG consisting of a long-sleeve cotton/polyester jacket (a mesh linear sewn with a main fabric) and full-length cotton/polyester pants was selected (see Fig. 1). Both the jacket and pants were incorporated with PCM packs and air ventilation fans. Eighteen PCM packs were placed into the 18 separate pockets (made of polyester mesh fabrics) stitched on the mesh linear of the jacket (i.e., 4 packs at the upper arms region, 6 at the chest and 8 at the back). Two ventilation fans were embedded to the lower back region. For pants, six PCM packs were inserted into the pockets of the pants at the thighs region, and two air ventilation fans were installed at the lateral pelvis area.

The main ingredients of PCMs are a mixture of sodium sulphate and water ($Na_2SO_4 \cdot 10H_2O$ known as the Glauber's salt) and additives. Its melting temperature and latent heat of fusion are 21.0 °C and 144 kJ/kg, respectively [35]. The weight and covering area of each PCM pack are 86 g and 92.4 cm^2, respectively. Thus the total weight and total covering area of the 24 PCM packs (i.e., 18 in the jackets and 6 in the pants) are 2.064 kg and 2217.6 cm^2, respectively. Each fan has a maximum flow rate of 12 l/s and its diameter is 10 cm. The total weight of the PCG including the main fabric of the garment is 3.589 kg. To facilitate the best cooling performance, the PCG was made with the bottom hems of the jacket and the