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A study on local cooling of garments with ventilation fans and openings placed at different torso sites

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ABSTRACT

The aim of the study was to examine the various design features of ventilated garments on cooling performance. Five jackets with small ventilation units and closable openings were designed. The ventilation units with a flow rate of 12 l/s were placed at five different torso sites. They were examined on a sweating thermal manikin in four clothing opening conditions in a warm environment ($T_a = T_{manikin} = 34$ °C, RH = 60%, $V_a = 0.4$ m/s). Total torso cooling was increased by 137–251%, and clothing total dynamic evaporative resistance was decreased by 43–69%. Neither the ventilation location nor the opening design had a significant difference on total torso cooling. The ventilation location had a significant difference on localized intra-torso cooling, but not the opening design. When the ventilation units were placed at the local zone where it was ventilated, that zone underwent the highest cooling than other local zones. The study indicated that the ventilation units should be placed at the region where it required the most evaporative cooling, e.g. along the spine area and the lower back. The openings could be adjusted (closed or opened) to make comfortable air pressure for the wearers but without making significant difference on the whole torso cooling under this flow rate.

Relevance to industry: Heat strain is frequently reported in hot environments, especially for those industries, such as construction, mining and steel. Clothing equipped with the small ventilation units could circulate the ambient air around the body and thus decrease heat strain and improve productivity.

1. Introduction

In hot working environments, people are inclined to be exposed to heat-induced threats (ISO 7243, 2003; Kjellstrom et al., 2009), particularly for those industries where personal protective clothing is required for safety reasons (Holmér, 2006; Bernard and Matheen, 1999; Bishop et al., 1995). The micro-environment under the protective clothing will generally be hotter and more humid than the ambient environment (Bishop et al., 2000). To protect people from heat stress and preserve productivity, various cooling technologies incorporated in clothing have been developed, e.g. cooling garments incorporated with phase change materials (PCMs) (Gao et al., 2010, 2011; Choi et al., 2008; Chou et al., 2008; Webster et al., 2005), garments with external connections to provide liquid (Kim and LaBat, 2010; Kayacan and Kurbak, 2010) or air cooling (Kuklane et al., 2000).

Cooling garments with small ventilation units powered by batteries can circulate the ambient air around the body. The ventilation units can be incorporated in the clothing without external connections to the power source. When the temperature and humidity of the ambient air are lower than the temperature and humidity of the skin, they enhance heat loss by convection and sweat evaporation (Xu and Gonzalez, 2011). Thereby, such ventilated cooling garments have been reported effective in hot environments or under highly insulated protective clothing to alleviate heat strain (Barwood et al., 2009; Hadid et al., 2008; Chinevere et al., 2008).

In the hot environments, especially when air temperature exceeds skin temperature, evaporative cooling might become the only way to dissipate heat. Sweat evaporation provides a powerful cooling mechanism in warm environments, taking up 0.68 W s (0.58 kcal) heat for each gram of water vaporized (Nunneley, 1989). The role of clothing acts as protection and at the same time acts as sweat evaporation

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barrier (Havenith et al., 1999). The amount of sweat vaporized from the skin surface to the ambient environment is closely related to clothing evaporative resistance (Havenith et al., 1999). The clothing evaporative resistance is largely affected by clothing design features, e.g. sizes, openings and materials (Chen et al., 2004; Li et al., 2007; Ho et al., 2011). Air motion and body movement can also change clothing evaporative resistance (Ho et al., 2011; Wang et al., 2012b). Up to date, very few studies have been carried to investigate the design features of the ventilated garment, e.g. ventilation location, air flow rate, etc. on its evaporative resistance and cooling performance. Therefore, it is desirable and meaningful to carry out a study to find out this.

In this study, a set of cooling jackets equipped with forced air ventilation were designed with the ventilation units placed at different torso sites of the garments. They were tested under different clothing opening conditions on a sweating thermal manikin. The aim was to explore torso cooling effect under the various ventilation designs and thus provide reference and guidance for industrial designers and end users.

2. Method

2.1. Ventilation garments design

The ventilated garment consisted of a short sleeve jacket and two ventilation units. Each ventilation unit was a small fan with a diameter of 10 cm (Hongming, Japan). They were powered by four AA batteries of 2300 mAh. The portable fans were embedded and locked in the jackets each by a plastic ring. When they were turned on they could circulate the ambient air around the torso at a flow rate of about 12 l/s (0.012 m^3/s). Five ventilated jackets were designed with the fans located at different torso sites (Fig. 1). All the five jackets were of the same sizes. They were made from the same fabric (80% cotton and 20% polyester, twill woven).

The bottom hems of the jackets were sewn with elastic straps, which made the jackets' bottoms fit the buttocks tightly. Three extra openings of air exchanging channels were designed with zippers. Two openings each with a length of 15 cm were at the chest and another opening with a length of 40 cm was at the upper back (Fig. 1). The thermal insulation and evaporative resistance of the whole ventilation jacket (the fans were turned off and zippers were closed) were 0.74 clo (0.114 m^2 °C/W) and 0.0173 kPa m^2/W, respectively.

2.2. Test combinations

Since clothing openings could influence the pathway of air flow and affect ventilation cooling, the five jackets were tested in four opening conditions to assess the various ventilation designs. The four opening conditions were presented as following:

Normal opening (NO). Openings at the collar and cuffs were opened, but the chest and back openings were closed (Fig. 2(a)).

Front opening (FO). Just the chest openings were opened. Openings at collar and cuffs were sealed by strings, and back opening was closed (Fig. 2(b)).

Back opening (BO). Just the back opening was opened. Openings at collar and cuffs were sealed by strings, and chest zippers were closed (Fig. 2(c)).

Both front and back openings (FBO). Zippers at chest and back were opened, but openings at the collar and cuffs were sealed by strings (a combination of (b) and (c) in Fig. 2).

Each of these five ventilated garments was tested in the four opening conditions, respectively. Totally there were 20 test scenarios.

2.3. Experimental protocol

A dry heated thermal manikin, Tore, with 17 individually controlled zones was used (Gao et al., 2010). A torso fabric skin (100% cotton knitted, area weight of 135 g/m^2) that fitted Tore tightly was made to simulate torso sweating. It covered four zones of the torso: chest, belly, back and buttocks. The fabric skin was pre-wetted by tap water and was fully saturated without water dripping by the approach described in our previous studies (Wang et al., 2011; 2012a). The moisture content in the fabric skin was about 147% of the initial mass. The manikin surface temperature was controlled at 34 °C. The climate chamber was set at 34 °C and relative humidity of 60%. Air velocity was kept at 0.4 m/s.

The manikin controlling system recorded the manikin surface temperature and heat loss of each zone every 10 s. A weighing scale (Mettler Toledo K240 connected to GWB Mettler ID2 MultiRange, Albstadt, Germany; accuracy ±2 g) was used to determine the evaporative rate of the moisture leaving the manikin-clothing system (Wang et al., 2009). The scale's software program recorded real time mass loss at 10 s intervals. Eight thermocouples (copper-constantan, data logger; Testo 176-T4 AG, Germany) were used to measure the fabric skin surface temperature (Wang et al., 2012b). They were attached at eight local sites: lateral upper chest, lateral belly, lateral upper back and lateral lower back. Each of the 20 scenarios was tested at least for three times and average values were used.

2.4. Calculation and analysis

Torso heat loss, Q, in W/m^2, was calculated by Equation (1). It was area weighted by the four localized zones. A is the sweating area and equals to the manikin torso area, 0.57 m^2, since the fabric skin is pretty thin and fits the manikin tightly. A_i is the area of each localized zone, m^2. Q_i is the heat loss measured on each zone, W/m^2.

$$Q = \sum f_i(Q_i) = \sum \frac{A_i(Q_i)}{A} \quad (i = 1, 2, 3, 4) \tag{1}$$

Total dynamic evaporative resistance of the ventilated garments (including that of the fabric skin), R_{et}, kPa m^2/W, in each condition

Fig. 1. Ventilated jackets with small fans and openings located at different torso sites. Both fans placed at (a), the upper back (UB); (b), the lower back (LB); (c), the mid back (MB); (d), the chest (upper front, UF); (e), the belly (lower front, LF).