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Evaluation of the Performances of Electrically Heated Clothing

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Evaluation of the Performances of Electrically Heated Clothing

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Department of Design Sciences

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Cover illustration: Infrared thermoimages of an electrically heated vest (EHV) with a heating power of 13.0 watts at an ambient temperature of 4.5 $^{\circ}$C.

Butchering a seal, again,
was no comfort in draughty wind-clothes and
temperatures well below zero, and
the numbness of our hands was the
cause of many cuts. . .

Contents

List of publications

This licentiate thesis is mainly based on the following papers:

Paper I. Wang F, Gao C, Kuklane K, Holmér I. A Review on Technology of Personal Heating Garments, *International Journal of Occupational Safety and Ergonomics (JOSE)*, **16** (3), 387-404 (2010).

Paper II. Wang F, Lee H. Evaluation of an Electrically Heated Vest (EHV) Using Thermal Manikin in Cold Environments, *Annals of Occupational Hygiene*, **54** (1), 117-124 (2010).

Paper III. Wang F, Gao C, Holmér I. Effects of Air Velocity and Clothing Combination on Heating Efficiency of an Electrically Heated Vest (EHV): A Pilot Study, *Journal of Occupational and Environmental Hygiene*, **7** (9), 501-505 (2010).

The above papers presented in this licentiate thesis were reprinted with kind permissions from the following publishers or institutes:

Paper I: Central Institute for Labour Protection (CIOP) in Warsaw, Poland;

Paper II: Oxford University Press in Oxford, UK;

Paper III: Taylor & Francis in Philadelphia, USA.

In addition to the publications included in this thesis the author has also contributed to the following papers:

Paper IV. Wang F. A Comparative Introduction on Sweating Thermal Manikins 'Newton' and 'Walter'. *Proceedings of 7th International Manikin and Modelling Meeting (7I3M)*, Coimbra, Portugal, 2008, pp. 1-7 (CD).

Paper V.   Wang F, Gao C, Kuklane K, Holmér I. A Study on Evaporative Resistance of Two New Skins Designed for Thermal Manikin 'Tore' Under Different Environmental Conditions, *Journal of Fiber Bioengineering and Informatics*, **1** (4), 301-305 (2009).

Paper VI. Wang F, Zhou X, Wang S. Development Processes and Property Measurements of Moisture Absorption and Quick Dry Fabrics. *Fibres & Textiles in Eastern Europe,* **17** (2), 46-49 (2009).

Paper VII. Wang F. Comparisons on Thermal and Evaporative Resistances of Kapok Coats and Traditional Down Coats. *Fibres & Textiles in Eastern Europe*, **18** (1), 75-78 (2010).

Paper VIII. Wang F, Wang S. Characterization on Pore Size of Honeycomb-patterned Micro-porous PET Fibers using Image Processing Techniques, *Industria Textila*, **61** (2), 66-69 (2010).

Paper IX. Wang F, Ji E, Zhou X, Wang S. Empirical Equations for Intrinsic and Effective Evaporative Resistances of Multi-layer Clothing Ensembles, *Industria Textila*, **61** (4), 176-180 (2010).

Summary of included papers

Paper I

Modern fibre and electronic technology makes it possible to make smart garments, which can help wearers to manage in specific situations by improving the functionality of traditional garments. The personal heating garment (PHG) widens the operating temperature range of garment and improves the protection against cold. Paper I describes four types of personal heating garments and their advantages and disadvantages are presented. Some challenges and suggestions are finally addressed with regard to the further development of personal heating garments.

Paper II

In Paper II, the heating efficiency of an electrically heated vest (EHV), its relationship to the microclimate temperature distribution in a three-layer clothing ensemble, and the effect of an EHV on the clothing's total thermal resistance were investigated by both theoretical analysis and thermal manikin measurements. It was found that the EHV can alter the microclimatic temperature distribution of the three-layer clothing ensemble. The EHV can provide an air temperature of 34 °C around the manikin's torso skin. The highest temperature on the outside surface of the EHV was around 38 °C, which indicates that it is safe for the consumer. The higher the heating temperature, the lower the heating efficiency obtained. This was due to much more heat being lost to the environment, and hence, the heat gain from the EHV was smaller. The heating efficiency decreased from 55.3 % at 0 °C to 27.4 % at -10 ℃ when the heating power was set at 13 W. We suggest adjusting the heating power to 5 W (step 1) at an ambient temperature of 0 °C, while at -10 ℃ using 13 W (step 3) to provide wearers a thermal comfort condition.

Paper III

Paper III presents a method based on a thermal manikin to investigate the effects of air velocity and clothing combination on the heating efficiency of an electrically heated vest (EHV). An infrared thermal camera was used to detect surface temperature distributions of the EHV on both front and back sides. The results show that the heating efficiency of the EHV decreases with increasing air velocity. The changes in EHV sequence in the three-layer clothing combination also significantly affect the heating efficiency: it increases with the increasing number of layers on top of the EHV. The highest mean temperature on the inner surface of the EHV was 40.2 °C, which indicates that it is safe for the wearers. In order to enhance the heating efficiency, we suggest that it should be worn as a middle layer. Finally, the EHV is especially suitable for occupational groups whose metabolic rate is below 1.9 Mets at an ambient temperature of 4.5 °C.

Abstract

Cold weather garments are necessary for people who are exposed to cold environments (below -5 °C). The weight and bulkiness of such a cold weather clothing ensemble may limit human activity and reduce the productivity. In order to solve these problems, a slim garment with a built-in heating element could be useful. The heat input power and heating efficiency are the two most important parameters for a piece of heated clothing. The input power determines how much heat can be released from the whole clothing system, while the heating efficiency demonstrates how many percent of the thermal energy could effectively contribute to wearers. However, previous studies have mainly focused on heat input power and there is a lack of knowledge about the heating efficiency of the heated clothing.

In this thesis, performances of electrically heated garments were compared and evaluated on two thermal manikins. The factors that affect on the clothing heating efficiency were thoroughly studied. It was found that the ambient temperature (or temperature gradient), air velocity and clothing combination can significantly influence the heating efficiency of a heated garment. In order to make good use of the thermal energy, the heating power should be well adjusted according to the environmental conditions. The heated clothing sandwiched between underwear and jacket in a three-layer clothing ensemble is one of the most effective ways to enhance the heating efficiency. In addition, the heated clothing alters the thermal evenness of clothing ensemble due to the heat release. This gives further evidence that the serial calculation method of clothing thermal resistance does not work for heterogeneous clothing ensembles.

Key words: cold weather clothing, electrically heated vest (EHV), thermal resistance, heating efficiency, air temperature, air velocity, clothing combination

Acknowledgements

The experiments presented in this licentiate thesis have been carried out at two universities: Sports Leisure Textile Research Centre in Inha University (Incheon, South Korea), and the Thermal Environment Laboratory in Lund University (Lund, Sweden).

It is my great pleasure to thank so many people who made this thesis possible.

Introduction

Clothing acts as a thermal and moisture barrier between the human body and environments. Cold protective clothing will be needed to protect the body against cold stress in temperatures below 10 °C, and most likely below 0 °C (Havenith, 2009).   In order to provide sufficient protection for a human body, traditional cold weather clothes are made containing several clothing layers. They are usually heavy and bulky. There is no doubt that such a clothing ensemble could provide enough protection against cold stress. However, increased weight and bulk of the clothing ensemble may limit human body activity, reduce the finger dexterity and the productivity, and increase the work load and muscular strain (Dorman and Havenith, 2009; Holmér, 2009).Therefore, it is necessary to seek some alternative clothing techniques to solve those problems. An alternative is the application of heated clothing to replace some bulky clothing middle layers.

The current available heated clothing can be divided into four distinctive categories: electrically heated clothing, PCM (phase change material) heated clothing, chemical heated clothing, and fluid/air flow heated clothing (Marick and Farms, 1942; Shim, 1999; Chan and Burton, 1982; Wissler, 1986). The electrically heated clothing uses various heating elements to generate heat. For most of electrically heated garments, a heating wire is used and is connected to an internal battery system or an external power supply. An obvious drawback is if one point of the heating wire is broken, the whole heating system doesn't work anymore; PCM materials such as paraffin and salt hydrates that are incorporated into clothing can release heat through changing the liquid phase to solid phase. The PCM materials can be either coated on the fabric surface or packaged in plastic bags and inserted in garment pouches. For PCM heated clothing, the amount of heat released largely depends on the

temperature gradient between the PCM melting/solidifying points and environmental temperature, and also, the mass of the material applied to a clothing system (Gao *et al.*, 2010); The chemical heated garment uses chemical reaction substances to produce heat, e.g., the chemical energy can be converted into the thermal energy by oxidisation. They are widely used in diving activities to protect divers in cold water. It is not easy to control the heating temperature for such a chemical heating system. Moreover, it might cause skin burns if the reaction temperature is too high; The fluid/air flow heated garment has a liquid/air circulation tubing system inside the garment by embedding soft tubes or other hollow mediums. Since water has good heat enthalpy and is nontoxic, it is frequently used in a flow heated garment. One of the most obvious disadvantages is that the tubing system would make the clothing stiff and it might also limit the human activity.

Perhaps an electrically heated garment is one of the most common heated garments (Wang *et al.*, 2010). The built-in heating elements can be flexible electrical element wires, graphite elements, electrically conductive rubber, textile fabrics treated in metallic salt solutions, polyethylene mixed with carbon black, or printed circuit heaters (Haisman, 1988; Wiezlak and Zielinski, 1993). Not so long ago, a new carbon polymer heating element made from bio-thermal carbon fibres was successfully developed and launched on the market. This heating element is slim, light and washable, and most importantly, there is no limit to human movement (Wang and Lee, 2010). Nowadays some high-tech conductive fibres appear to be used for heating elements in such a heated clothing system (e.g., WarmX® GmbH, 2010).

The attempts of incorporating electric heating elements such as heating wires to clothing are not new (Scott, 1988). One of the earliest documented applications on electrically heated clothing goes back to World War II (Madnick and Park, 1967). The bombers aircrews were equipped with electrical heated gloves to alleviate high-altitude frostbite. Since then,

electrically heated gloves and socks have been used by many occupational groups, such as missile fuel handlers (Bradford, 1960), arctic maintenance personnel (Roy, 1967), motorcycle drivers (Stuart, 1969), and hand workers (Ducharme *et al.*, 1999). However, Burton and Edholm (1955) pointed out that if the body torso is cooling, using of electrically heated gloves or socks to body extremities alone is useless and may be very dangerous. Thus they argued that it is more important to supply heat to the torso than to the extremities, i.e., it is more useful to apply heating elements to the human torso. On the other hand, many previous studies (Haisman, 1988; Santee *et al.*, 2000; Rantanen *et al.*, 2002) on the electrically heated clothing have been well revealed that the power for the whole heating clothing system is very important to prevent a decline in finger temperature or skin temperature. Furthermore, in this so called 'energy-saving era', energy efficiency becomes very most important to the whole society. The investigations on the heating efficiency of such a heated garment system are meaningful. Moreover, this topic is quite new and no previous study is available. Thus, this thesis will partly focus on proposing a definition of clothing heating efficiency and also, investigating parameters that influence the heating efficiency of the electrically heated clothing.

The heat transfer property of a protective clothing ensemble is vital to the wearer's heat balance, which may determine the human physiological performance (Havenith *et al.*, 2002). Clothing thermal resistance (or thermal insulation) is one of the most important inherent physical parameters to characterise its heat transfer property (Fan and Qian, 2004). The thermal resistance slows the heat transfer between wearers and the environments. This thermal protection provided by the garments can be divided into three important descending categories: survival, function and comfort (Santee *et al.*, 2000).

The thermal resistance of the fabric material or clothing can be measured on a 'flat' guarded hotplate, a thermal manikin (ISO 11092, 1993; EN ISO 15831, 2004), or on a human subject. (Afanasieva, 2000; Kuklane *et al.*, 2003; Konarska *et al.*, 2007) It has demonstrated that thermal manikin measurements provide a more realistic value than provided by a guarded hotplate (Ross, 2005). This is because thermal manikin tests are able to simulate the real body shape and also, to evaluate the effects of garments' boundary air layer. In addition, thermal manikin measurements could also take into consideration of clothing design features, which are also contributed to the clothing evaporative resistance. For the human subject trial method, however, it is costly and the test conditions should be more carefully controlled. Also, the ethic issues on human experiments are involved. Furthermore, the human subject measurement error (12-18 %) is much higher than the error on a thermal manikin (2 %). Thus, the thermal manikin is a good intermediate tool to bridge the big gap between the guarded hotplate (i.e., a flat apparatus) and the physiological testing (3D testing).

Thermal manikins have been applied to many research areas such as clothing physiology and environmental ergonomics for almost 70 years (Holmér, 1999). There are more than 100 thermal manikins in use worldwide. They are mostly in use in Canada, United States, Belgium, Denmark, Finland, France, Germany, Hungary, Poland, Portugal, Netherlands, Norway, Sweden, Switzerland, United Kingdom, China, Japan and South Korea (McCullough, 2009). In this thesis, two thermal manikins were applied to evaluate the performances of electrically heated clothing.

Aim

The main aim of this thesis is to assess the performances of electrically heated clothing. Two electrically heated vests were selected for experiments. The parameters that influence the heating efficiency of two electrically heated vests were investigated.

The main purpose of paper I was to present a thorough overview on four categories of personal heating clothing (PHC). The heating technology and features of different heating garments were described. Some suggestions on how to further assess the performances of PHC were finally addressed.

The main purpose of paper II was to evaluate the performances of an electrically heated vest (EHV) within a three–layer cold protective clothing ensemble. The effect of environmental temperatures on the heating efficiency of the EHV was investigated. Moreover, thermal resistances of the whole clothing ensemble with and without heating power were calculated by the parallel and serial methods.

The main purpose of paper III was to examine the effects of air velocities and clothing combinations on the heating efficiency of the EHV. Some future studies on how to further evaluate the performances of the EHV on human subjects were discussed.

Methods

Clothing ensembles tested

In paper II, a typical three-layer clothing ensemble was selected for the study. It includes a pair of long trousers, a set of underwear, an electrically heated vest, a jacket, a pair of gloves and a pair of sports shoes.
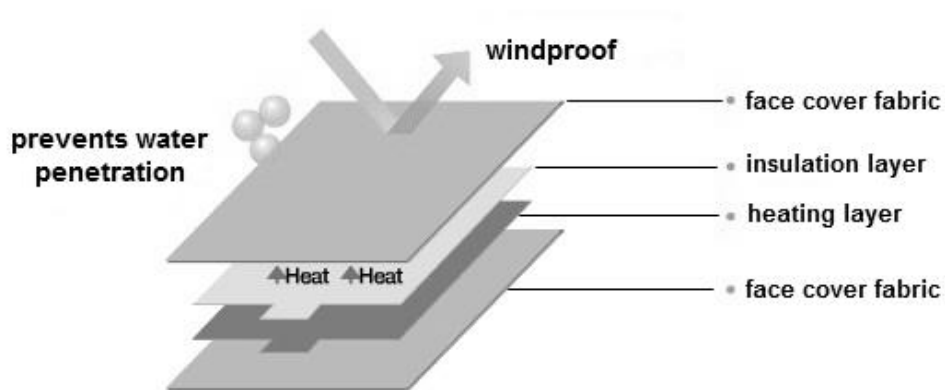
Figure 1 The structure of a built-in heating element (©Kolon Glotech Inc., 2008).

The built-in heating element is made from conductive textiles. An innovative technology integrates the electronic and textiles tightly through depositing conductive materials on fabric. It has a typical 4-layer structure: front face cover fabric, insulation layer, heating layer and the back face cover fabric. Moreover, it is multi-functional: heating, waterproof, windproof, flexible and lightweight. The structure of the heating element is presented in Figure 1.

In paper III, a set of military uniforms, an article of knit cotton underwear, a pair of thick polyamide stockings, a pair of sports shoes, a pair of thick gloves, and an electrically heated vest (EHV) were used. Totally six strips of heating elements embedded in the EHV. They are made from high-performance carbon microfiber. The total weight of the EHV is 514 g. The total heating area accounted for 8.5 % of the total manikin torso surface area. The location of

all six heating elements inside the EHV is displayed in Figure 2. The details of all garments used in this thesis are described in Table 1.
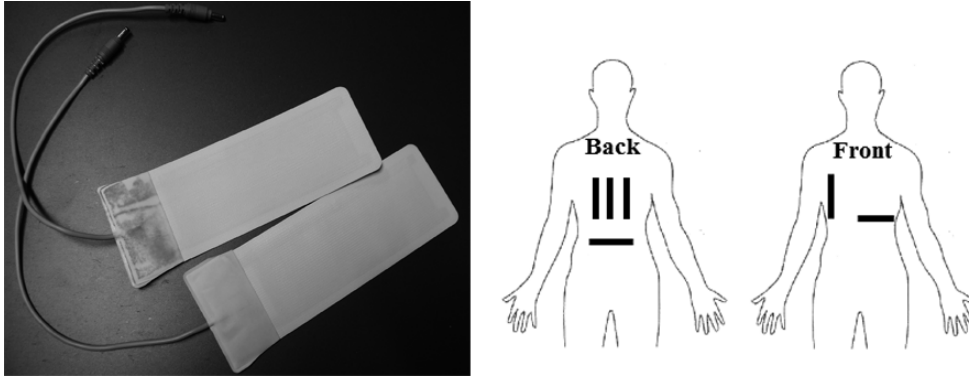
Figure 2 The built-in carbon heating elements and their locations inside of a vest.

Table 1 Details of clothing ensembles.

Study	Garments	Details
	underwear	coolmax® fabric
	EHV	polyester woven vest with 100 % batting
II	jacket	Gore-tex® with 100 % nylon lining
	gloves	cotton
	trousers	polyester
	sports shoes	light weight Gore-tex with mesh detail
	Underwear (code: U)	Cotton
III	EHV (code: E)	polyester/spandex
	Uniform (code: M)	polyamide/cotton
Unpublished	Down vest (code: TDV)	Shell: nylon, lining: polyester filler: goose down
	Taiga jacket	52 % cotton, 48 % nylon
	EHV	polyester/spandex

In an unpublished study, a Taiga® jacket, an EHV and a down vest were selected for measurements. The EHV used in this study was the same as the one used in paper III. Three levels of heating power for the EHV were used: 9.0, 13.9, and 24.7 W.

Thermal manikins

a) 'Newton'   b) 'Tore'

Figure 3 The front view of two thermal manikins.

In study II, a thermal manikin 'Newton' (Wang, 2008) was used. It is constructed of a conductive aluminium filled carbon-epoxy shell with embedded heating and sensor wire elements. 'Newton' is fully jointed and is allowed to make any virtually body pose. The total body surface area is 1.81 m^2 and the whole manikin weighs 30 kg. This manikin has 20 segments for which the manikin surface temperature was controlled independently, and the total heat input required to achieve this was measured accurately. The heat input is a direct measure of the heat loss from the manikin. The manikin surface temperature and heat loss of each segment were obtained from the MTNW's (Measurement Technology Northwest, Seattle, WA, USA) ThermDAC software.

In study III and the unpublished study, a dry heated thermal manikin 'Tore' (Kuklane *et al.,* 2006) was used. 'Tore' is made of plastic foam with a metal frame inside to support body parts. Its height is 170 cm, chest and waist circumferences are 94 and 88 cm respectively, with total heated body area of 1.774 m^2. The whole manikin weighs 33 kg.

Test conditions

The study II and study III were designed to examine the effects of air temperature, air velocity and clothing combinations on the heating efficiency of two electrically heated vests. In study II, two typical environmental temperatures were chosen: 0 °C (cold) and -10 °C (very cold). Two levels of heating power were selected for the electrically heated vest: step 1 (5.0 Watts) and step 3 (13.0 Watts). The study III was conducted at a slightly cool environment and three different levels of air velocity were selected. The heating power of the EHV was set to 13.0 Watts. The experimental conditions are summarised in Table 2.

Table 2 Details of experimental conditions.

Study	Air temperature °C	Relative humidity %	Air velocity m/s	Manikin surface temperature °C
II	0.0±0.5 -10.0±0.5	30±5	0.40±0.10	33.0
III	4.5±0.5	85±5	0.22±0.08 0.44±0.09 0.66±0.09	34.0
Unpublished	16.0±0.5	40±5	0.40±0.10	34.0/ 30.0

An unpublished study on comparison of the insulating property of a traditional down vest (TDV) and an EHV was also presented. The thickness of a TDV (The North Face, weight: 500 g) and an EHV (Bandy, South Korea) was roughly measured by an electronic digital calliper (Welleman DCA 150, resolution: 0.01 mm, measuring length: 0-150 mm). The torso dry heat losses from the thermal manikin 'Tore' when worn a TDV and an EHV with different heating powers were calculated. For the EHV, two heating input powers were chosen, 13.9 and 24.7 W. The manikin surface temperature was controlled at 34.0 °C or 30.0 °C.

Calculation options

Heating efficiency

For a heated clothing system, the heating efficiency η of the whole electric circuit is defined as

$$\eta = \frac{\Delta HL_{area}}{P_{sup\,ply} \cdot k} = \frac{\sum_{i=1}^{n} H_i A_i}{P_{sup\,ply} \cdot k} \tag{1}$$

where, $\Delta HL_{area,}$ is the decrease in the area-weighted heat loss (in Watts) from the thermal manikin when the power supply is switched on, compared with when it is switched off. As explained above, the heat loss from the manikin is measured as the power that must be used to maintain the manikin's constant temperature. H_i, is the decrease in the amount of heat goes to the segment, i (W/m^2); A_i, is the surface area of the segment, i (m^2); P_{supply}, is the output power of the battery or an external power supply box (W); k is the energy conversion rate of the heating element, %. This conversion rate may be slightly different from one heating element material to another. For instance, the conversion rate of the carbon polymer heating element used in study II is 90 %, while in study III of another type of heating element, it is 100 %.

Thermal resistance

In study II, clothing thermal resistances were calculated by two methods as defined in EN ISO 15831 (2004): the parallel method and the serial method. The parallel method determines the thermal resistance as an area-weighted average of the local thermal resistance. The serial method is based on the measurement of total thermal resistance by summation of the local thermal resistances. These two methods are given by

$$R_{tp} = \frac{\left[(\sum_{i=1}^{n} \frac{A_i}{A} \cdot t_{ski}) - t_a \right]}{0.155 \times \sum_{i=1}^{n} H_i} \quad (2)$$

$$R_{ts} = \sum_{i=1}^{n} \frac{A_i}{A} \times \left[\frac{(t_{ski} - t_a) A_i}{0.155 H_i} \right] \quad (3)$$

where, R_{tp} is total clothing thermal resistance calculated by the parallel method, clo; A_i and A are the surface area of the manikin zone, i, and the total surface area of the manikin respectively, m^2; t_{ski} and t_a are the local skin surface temperature of the zone, i, of the manikin and air temperature respectively, °C; H_i is the local heat loss of the zone, i, of the thermal manikin, W; R_{ts} is the total clothing thermal resistance calculated by the serial method, clo.

Statistical analysis

All manikin experiments were repeated twice for each test condition. The data were expressed as mean ±SD (standard deviation). In study III, a two-way ANOVA (analysis of variance) was performed using a statistical program (SPSS v16.0, Chicago, IL, USA) to examine whether the effects of air velocity and clothing combination on the heating efficiency of the heated vest were significant. The significance level was $\alpha = 0.05$.

Results and Discussion

Comparison of the insulating property of a TDV and an EHV

This section presents some unpublished results on comparisons of the insulating property of a TDV and an EHV. According to the definition of clothing thermal resistance presented in equations (2) and (3), the numerators are the same if two tests were conducted in the same test conditions (i.e., the same thermal manikin, ambient conditions, and the same manikin set temperature). Therefore, the total dry heat loss (i.e., the denominator) from the thermal manikin at the same test condition can reflect the insulting property of a garment. The torso heat losses from the manikin 'Tore' at different test conditions were displayed in Figures 4 and 5.

The thickness of TDV and EHV are 40.5 and 6.5 mm, respectively. Hence, the TDV is more than six times thicker than an EHV. On the other hand, it can be deduced from Figure 4 that the TDV has almost the same insulating property as the EHV with a heating power of 13.9 W at 16 ºC. The higher heating power of the EHV at the same ambient temperature, such as 24.7 W, could contribute much heat energy to the manikin. Thus, the total torso heat loss was lower and such an EHV with this specific heating power has better protection than the TDV. Furthermore, if the manikin surface temperature was set to 30 °C, the torso heat loss from the manikin in the EHV with a heating power of 9.0 W was the lowest of all due to the temperature gradient between the manikin surface and the environment was 4 ^{o}C lower than other test conditions. Similarly, if an additional layer was covered over the EHV, such as the EHV (9.0 W) covered with a Taiga® jacket on the top, the total heat loss was largely decreased by 50 % due to that much more thermal energy from the EHV effectively went to the manikin.
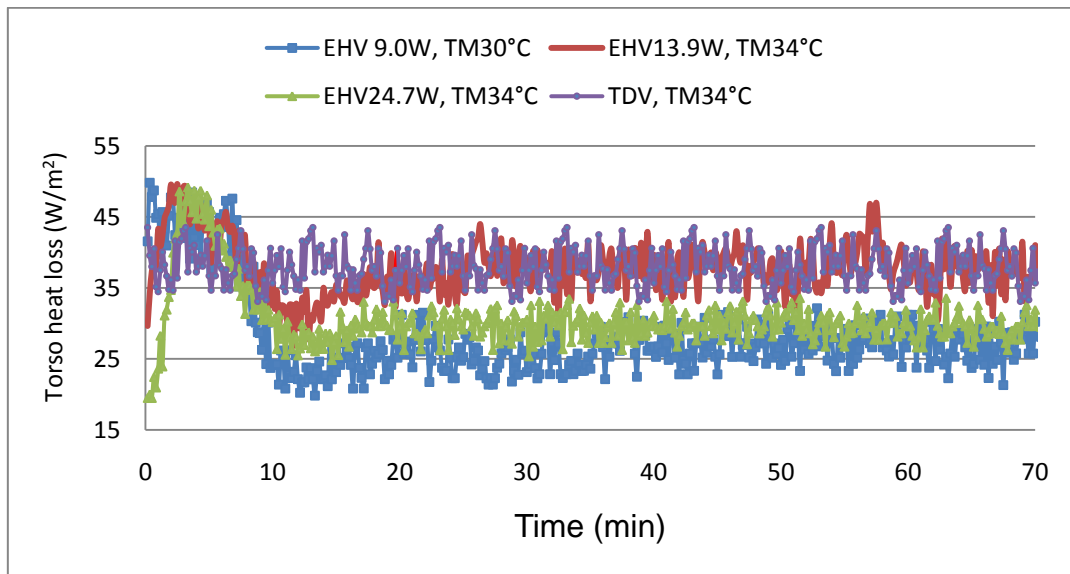
Figure 4 Total area weighted torso heat losses from the manikin in different clothing. TM, the thermal manikin surface set temperature.
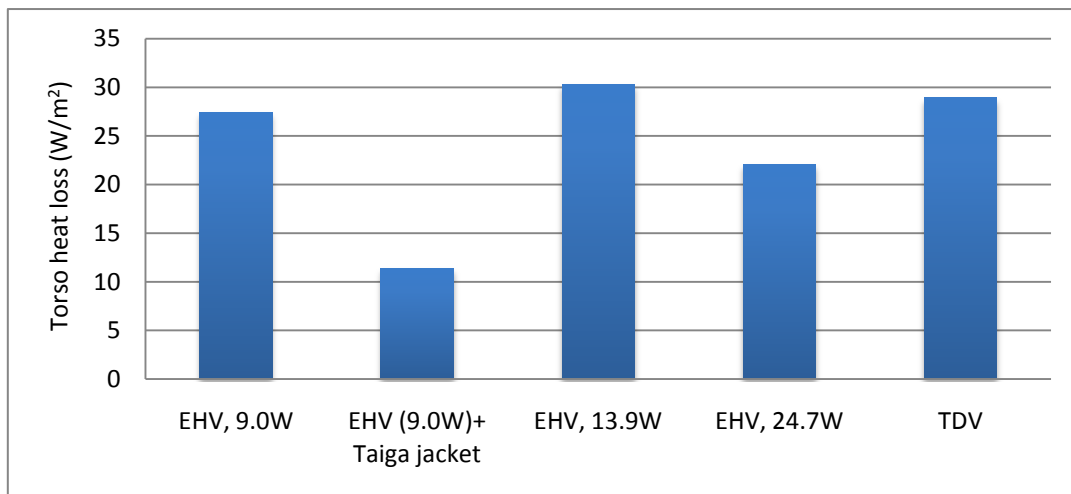
Figure 5 Comparisons of torso heat losses from the manikin in the EHV with different input powers and the TDV. The manikin surface temperature was maintained at 34 °C except the EHV with a heating power of 9.0 W ($T_{manikin}$=30 °C).

Summary of results and discussion of study II

The thermal resistances calculated by the serial method for the whole clothing ensemble with heating power (5 watts in step 1, 13 watts in step 3) show significant differences

compared with values without heating power, especially when the heating power is set at 13 watts in step 3. This is because the EHV changes the evenness of the 'dynamic thermal resistance' distribution of the whole clothing system. Thus, the serial method overestimates the effect of the actual resistance when measured on a thermal manikin with homogenous surface temperature distribution. It is concluded that the serial calculation method does not work with extremely heterogeneous clothing ensembles and heated garments. Also, the serial method is totally wrong from a physical point of view (personal communication, 2010). This finding is in agreement with previous studies reported by Kuklane *et al.* (2007) and Holmér *et al.* (2009).

Compared with no heating, the EHV with heating power greatly increased both the temperatures on the surface of the vest and between the vest and jacket by up to 10 °C at 0 °C. The temperature between the skin surface and underwear was increased by 4 °C. However, there was no significant change of temperatures on the underwear and between the underwear and vest. The heat fluxes are apt to move in the direction of the outside clothing due to the low temperature there causes a larger temperature gradient in that direction. The temperature on the back side of the EHV at its highest heating power (step 3) was about 38.0 ℃, indicating that it is safe for human skin (Greenhalgh *et al.*, 2004). Similarly, temperatures on the surface of the vest, between the vest and jacket, and between the skin and underwear increased by about 4 to 12 °C compared with no heating at the test temperature of -10 °C. The highest temperature on the back side of the EHV at step 3 was still around 38.0 °C. However, the mean temperature on the outer layer surface of the EHV decreased by 5 °C compared with that of 0 ℃. The average microclimate temperature between the skin and underwear was still about 34 ℃, which indicates that the EHV could provide a thermal neutral condition for the consumers even at -10 ℃.

The EHV changed the microclimate temperature distributions for both of two heating powers. The air layer temperature next to the skin was about 34.0 ℃, which demonstrates that the EHV can provide the human skin in a thermal comfort condition (Fanger, 1970) in cold environments. The mean outer surface temperature of the EHV with a power of 13 watts increased by 12 °C compared with that of no heating power at 0 °C. For an ambient temperature of 0 °C, the heating power at 5 watts is enough to keep the torso of the wearer in thermal comfort. However, such a heating power (5 watts) for the EHV at -10 °C cannot keep the manikin torso in a thermal comfort condition. As a result, the heating power of the EHV should be set in step 3 at -10 °C to generate sufficient heat for the wearer to approach a better thermal condition. Finally, the ambient temperature affects heating efficiency. Much more heat is lost to the environment, making the heating efficiencies at -10 °C much lower than at 0 °C. The heating efficiency of the EHV with a heating power in step 1 of 0 °C is higher than that of step 3 at the same heating power. While the efficiency at step 1, -10 °C is lower than at step 3. This latter condition is probably caused by the fact that the temperature gradient between the vest and the ambient at 0 °C is 5 °C higher than that at -10 °C.

Summary of results and discussion of study III

The heating efficiency of the EHV in three different clothing combinations decreases with increasing air velocity within the tested short air velocity intervals (0.22-0.66 m/s). The maximal heating efficiencies in the three clothing combinations at 0.22 m/s were 0.9 to 6.0 % greater than the values obtained at other two levels of air speed: 0.44 or 0.66 m/s. The explanation for this is that greater air velocity results in more heat energy from the EHV dissipating to the environment. The air velocity has the greatest influence on the heating efficiency of the EHV in clothing combination U+E+M (U+E+M stands for clothing U worn as an inner layer, E as a middle layer, and M as the outer layer), and the least in U+M+E. This

is because the M clothing is loose and allows higher air ventilation through both sides of the EHV in the U+E+M, while the EHV in the U+M+E combination is tighter fitting to U and M: the air can only go through the outer surface of the EHV. Hence, there should be more clothing layers on top of the EHV and all clothing openings should be closed in order to gain sufficient heating benefit from the EHV under strong winds. Moreover, the statistical results also showed that both the air velocity and clothing combination have significant direct influences on the heating efficiency of the EHV. The calculated maximum theoretical heating efficiencies of the EHV in clothing combinations E+U+M, U+E+M and U+M+E (assuming the air velocity is 0 m/s) were 78.6, 64.3 and 52.9 %, respectively. The EHV has the highest heating efficiency when it served as an inner layer in the three-layer clothing ensemble. On the other hand, the EHV has the lowest heating efficiency when it served as an outer layer. This is because the outer layers on top of the EHV provide an efficient thermal resistance to avoid the loss of too much heat from the EHV to the environments.

The *IREQ$_{neutral}$* index was used to determine the suitable occupational groups for wearing such an EHV in a three-layer clothing ensemble at an environmental temperature of 4.5 °C. For a person in clothing ensemble E+U+M at 0.66 m/s (*IREQ$_{neutral}$* equals the intrinsic thermal resistance of clothing combination E+U+M: 1.71 clo), the required metabolic energy production to keep thermal neutral was 108 W/m^2, i.e., 1.9 Mets. Thus this EHV is especially suitable for the wearers whose metabolic rate is below 1.9 Mets, such as workers sitting in an office without room heating facilities and occupational workers who carry out light activities, such as hand work (small bench tools, inspection, assembling or sorting of light materials) and arm work (driving vehicles, operating foot switches, light strolling). For the occupational groups whose metabolic production is above 1.9 Mets at 4.5 °C, the human body can produce enough heat to keep the body heat balance. Hence, it is not necessary to use such an EHV.

Conclusions

The performances of two electrically heated vests were evaluated on two thermal manikins. Some important conclusions are drawn below:

1) The electrically heated clothing can alter the thermal evenness inside clothing ensembles. This makes that the calculated thermal resistance by the serial method is much larger than that of obtained by the parallel method. However, the heat doesn't change the thermal resistance of the whole clothing ensemble. It was demonstrated that the serial method was not suitable to calculate thermal resistances of heterogeneous clothing ensembles. Therefore, the serial method should be removed from the ISO standard.

2) The ambient temperature (or temperature gradient), air velocity and changing of the sequence of the heated clothing inside a multi-layer clothing ensemble have significant effects on the heating efficiency of the heated clothing. The woven vest worn as an inner layer may influence the wear comfort and tactile comfort. Also, the heated clothing would lose much more energy if it was worn as an outer layer. Therefore, in order to enhance the heating efficiency of the heated clothing, it could be worn as a middle layer inside the clothing ensemble.

3) It is difficult to determine temperature ratings for such EHVs. The temperature rating ranges highly depend on the wearer's metabolic rate, the clothing worn on top the EHV, and the environmental conditions. This is different with the determination of temperature rating for sleeping bags (BS EN 13537, 2002).

Future Study

Fundamental research has been carried out to evaluate performances of electrically heated clothing on thermal manikins under steady states. However, cold weather garments are used by people more often in transient/dynamic conditions. This situation differs with the steady state. Some further investigations are suggested as follows:

Recently, there is a trend towards using thermal physiological models to regulated thermal manikins (Psikuta *et al., 2008*). The thermophysiological model controlled thermal manikin could determine thermal effects of personal heating or cooling systems (Bogerd *et al., 2010*). Therefore, a thermal manikin coupled with a human physiological model should be used to investigate the effect of a personal heating system such as an electrically heated vest on the manikin skin and core (e.g., rectal temperature) temperatures.

Furthermore, human subjects trials are required to verify the results obtained on thermal manikins. The effects of heated clothing on the skin temperature of human subjects should be examined. The suitable activity level for the subjects who wear such a heated clothing system that could maintain the heat balance at a specific cold environmental condition should also be determined. More types of heated garments with different built-in heating elements can be collected from current market for measurements to decide the one that has the most wear comfort sensation. This can greatly improve the product usability and also, guide consumers to choose their ideal clothing.

Finally, cold stress on people is generally not of an issue than heat stress in most areas worldwide. In this thesis, performances of the EHVs were studied and dry experiments on thermal manikins were conducted. However, those manikin dry tests might not be enough and further manikin and human subject studies are required. On the other hand, the evaporative

resistance is also a very important parameter or input for assessment of protective clothing and prediction of the heat strain on human beings. To determine clothing evaporative resistance, wet tests on sweating thermal manikins are required. Also, human subject trials should be performed to provide reliable validation data for thermoregulatory models. Future PhD dissertation will focus on the topic of moisture transfer through protective clothing ensembles and application of human thermal regulatory models to predict human physiological responses in various hot environments.

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Paper I

REVIEW

A Review of Technology of Personal Heating Garments

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Modern technology makes garments smart, which can help a wearer to manage in specific situations by improving the functionality of the garments. The personal heating garment (PHG) widens the operating temperature range of the garment and improves its protection against the cold. This paper describes several kinds of PHGs worldwide; their advantages and disadvantages are also addressed. Some challenges and suggestions are finally addressed with regard to the development of PHGs.

energy save   cold protection   personal heating garment (PHG)   human comfort

1. INTRODUCTION

As garments become smart, it is possible for people to protect their vital organs against cold stress in thermal neutral or comfort conditions both in foul weather outdoor environments and in indoor environments without heating facilities by improving the functionality of garments.

1.1. Cold Injury

Individuals in various occupations and people living in high-latitude regions are frequently exposed to cold stress that may result in cold injuries. Traditionally, cold injuries are divided into freezing and nonfreezing cold injuries [1]. A freezing cold injury (e.g., frostbite and frostnip) occurs where cooling lowers the temperature to the level where tissue fluid freezes. Nonfreezing cold injury, e.g., immersion foot, occurs when reduced blood flow after chilling and low temperature causes damage to nerves. Less severe injuries are cracked skin and chilblains caused by chilling of extremities, usually fingers, toes, and ears [2]. To reduce the risks of cold injury, people can wear a personal heating garment (PHG) to extend their exposure time in a cold environment and/or reduce cold stress.

1.2. International Standards

At present, Standards No. ASTM F 2300-05 and ASTM F 2371-05 are the only two standards on measuring the performance of personal cooling systems with sweating heated thermal manikins and physiological testing [3, 4]. There is still no international standard on evaluating of personal heating systems. Moreover, there are various kinds of personal heating garments (PHGs) on the market worldwide and they are expected to be very successful. Hence, it is necessary to develop an international standard to evaluate

the performance of these products and to guide people how to choose suitable personal heating systems.

1.3. Thermal Comfort

According to Standards No. ISO 7730:2005 and ASHRAE 55-74, thermal comfort is defined as being "that condition of mind which expresses satisfaction with the thermal environment" (p. 5) [5], (p. 4) [6]. Two conditions must be fulfilled to maintain thermal comfort [7]. One is that the actual combination of skin temperature and the body's core temperature provide a sensation of thermal neutrality. The other is the fulfilment of the body's energy balance: the heat produced by metabolism should be equal to the amount of heat lost from the body.

Macpherson identified six factors that affected thermal sensation [8]. These factors were air temperature, humidity, air speed, mean radiant temperature, metabolic rate and clothing levels. He also identified 19 indices for assessing the thermal environment. Each of them incorporates one or more of the six factors.

The Fanger comfort equation is the most common. It is based on experiments with American college-age persons exposed to a uniform environment under steady-state conditions [9]. The comfort equation establishes the relationship among the environment variables, clothing type and activity levels. It represents the heat balance of the human body in terms of the net heat exchange arising from the effects of the six factors identified by Macpherson. The Fanger comfort equation can be expressed as

$$
\begin{aligned}
&(M/A_{Du})(1-\eta)/-0.35[43-0.061(M/A_{Du}) \\
&(1-\eta)-P_a]-0.42[(M/A_{Du})(1-\eta)-50] \\
&-0.0023(M/A_{Du})(44-P_a) \\
&-0.0014(M/A_{Du})(34-T_a) \\
&=3.4\times10^{-8}f_{cl}\left[(t_{cl}+273)^4-(t_{mrt}+273)^4\right] \\
&+f_{cl}h_c(t_{cl}-t_a).
\end{aligned} \tag{1}
$$

It is clear from Equation 1 that human thermal comfort is a function of three types of parameters: (a) clothing parameters, which include clothing temperature t_{cl} and clothing area factor f_{cl}; (b) parameters of the human body, which include external activity efficiency η, human metabolic rate M and human surface area A_{Du}; and (c) environment parameters, which include air velocity V, air temperature t_a, mean radiant temperature t_{mrt} and air pressure P_a. Consequently, thermal comfort can be acquired by rationally controlling those three parameters.

1.4. Methods for Keeping Thermal Comfort

According to the Fanger thermal comfort equation, there are three main external approaches for people to stay at thermal comfort in cold environments. One is to stay indoors and rely on building heating which in developing countries means heat pumps, gas fireplaces or radiators used to heat rooms. In most countries, however, there is central heating, which uses electricity, oil or wood; there is also ground heating and air heating. People can benefit from the surrounding environment and keep their body temperature at an optimum temperature. However, heating buildings is expensive. Another approach is active heating with PHGs to keep the body warm. It can be expected that warming the microclimate around the body compared to heating the whole house can save much energy [10]. With increasing energy costs and awareness of excessive consumption, it is wise to use PHGs to keep the body warm in cold winters both indoors and outdoors. The third approach is to use traditional thick multilayer garments including footwear, gloves and hats, which is a passive heating method of preserving the body's own heat. People can wear several layers of high insulating garments to keep their bodies in a thermoneutral condition. However, it may be difficult to estimate the need for the required number of garments for various environmental conditions. Another problem is related to increased bulk of a clothing ensemble with a greater number of garments, which will limit body movement, manual dexterity and reduce human performance [11].

This review describes five types of PHGs; it analyses and discusses their advantages and disadvantages. Some future challenges and

suggestions are finally addressed on the design of these personal heating systems.

2. TYPES OF PHGs

2.1. Electrical Heating Garment (EHG)

Generally, electrical heating products use embedded heating elements to generate heat. In most EHGs, a single electrical heating wire is used; it is connected to a power supply. Some other possible heating elements for such EHGs are graphite elements, electrically conductive rubbers, neutralised textile fabrics, positive temperature coefficient polymers and carbon polymer heating fabrics [12]. The concept of applying electrical heating directly to a clothed individual is not new. Since the early days of electrical power, inventors have sought ways of using the heating effect of low voltage DC supplies. One of the most practical attempts to incorporate electrical heating into clothing dates back to World War II, when bomber air crews were equipped with leather flying jackets fitted with electrical element cables similar to those in electrical heating blankets [13].

In 1942 Marick developed electrically heated apparel [14]. The heating garment attempted to cover practically the entire body; it had electrical heating pads extended over a large portion of it. Two textile layers were used to protect heating element from damage.

Deloire, Durand and Mans developed a heating garment that minimally hindered the wearer's movements [15]; it could also distribute heat uniformly. The heating elements with good stretch properties were placed inside passages made by sewing two fabrics together along parallel lines. The heating wire was made of a resistance alloy and covered by extrusion with a layer of polyvinyl chloride which could withstand a relatively high temperature. Metcalf developed a vest-type garment with a lining consisting of an electrical heating element [16]. Sleeves, pants and a hat were also developed. A 6-V DC power source supplied electrical heating to the elements in each garment.

2.1.1. Testing EHGs

Kempson, Clark and Goff described the design, development and evaluation of electrically heated gloves for alleviating pain in vasospastic disorders [17]. They also assessed their effect on tissue perfusion in individual patients with thermography. They discovered that those gloves provided considerable benefit to patients suffering from Raynaud's phenomenon and related vasospastic disorders.

Haisman conducted several physiological evaluations and user trials on various types of electrically heated items [18]. Cold-chamber trials showed the effectiveness of electrical heating in maintaining hand temperatures and slowing the fall in foot temperatures even in the extremely cold climate of –32 °C. This field study survey indicated that users perceived the advantages of electrically heated clothing in terms of increased comfort and manual dexterity; however, they also pointed out disadvantages such as encumbrance, restriction of movement and durability problems.

The Naval Medical Research Institute conducted a study on the effects of electrical hand and foot heating on diver thermal balance [19]. Thirty-two divers in dry suits with M-600 Thinsulate™ undergarments were immersed for periods of up to 8 h in 3 °C water. The divers wore electrical resistance heated gloves and socks over polypropylene liners and under the Thinsulated insulation. Their hands and feet remained dry by communication with the dry suit. Water perfusion rate or electrical power was adjusted to maintain desired digit temperatures. The power required for warm-water heating averaged 211 W. The average electrical resistance heating power requirement was estimated as the product of dutycycle and continuous power available. The average electrical power delivered was 13.4 ± 3.4 W/hand and 9.8 ± 2.4 W/foot for 18 °C digit temperatures. Mean skin and rectal temperature decreased by 6 ± 2.2 and 1.2 ± 0.3 °C, respectively, during the 4-h immersion. Hand dexterity was improved by supplemental heating compared to the unheated group. No differences were observed in skin conductivity or whole

body heat loss between groups. Supplemental heating did not reduce the need for adequate passive whole body thermal insulation for long immersions in cold water. Supplemental heating reduced hand and foot discomfort at low energy cost, and reduced the decrement in manual dexterity compared to no heating. The low energy cost of resistance heating made this feasible for immediate use by the fleet.

Batcheller, Brekkestran and Minch designed a lightweight, stretchable electrically heated, cold weather garment [20]. Many flexible, electrical heating wires covers were stitched to the fabric. Kelvin, Kamyab, Nguyen, et al. were the first to use an electronic controller of current flow through each of the heating wires in a pulse-width modulated fashion, and independently control the heat generated by each heating wire [21]. A master power level potentiometer was used to control the power supplied to each heating wire in a uniform and simultaneous fashion. Kelvin et al. pointed out that it was necessary to control the heating rate independently at different parts of the body as heat loss from different body parts could vary considerably. In addition, physical activities of the wearer could cause different body parts to generate heat at various levels.

The Human Research and Engineering Directorate of the U.S. Army Research Laboratory conducted a pilot study to determine the level of thermal protection afforded by EHGs including a vest and gloves [22]. One objective of the study was to determine whether heated hand- and footwear alone could enhance thermal protectiveness of the extended cold weather clothing system (ECWCS) ensemble to a measurable and useful extent; another objective was to determine whether heated garments over body areas would improve the protectiveness of ECWCS, and by what amount the use of these garments would extend the period of effective cold protection. The test temperature was –40 °C and a 12-V DC power supply was used for the electrically heated components. They found that the use of electrically heated hand gloves and footwear substantially improved the thermal protection provided by the ECWCS uniform

ensemble of sedentary solders at –40 °C. The protection was greater for hands in heated gloves than those in extreme cold-weather mitten ensembles. The use of electrically heated body garments in addition to heated hand gloves and footwear did not improve the effective protective protection of the ECWCS uniform ensemble.

Roell made an electrical heating element in the form of a knit fabric, which included current supply and resistance wires [23]. The different types of wires extended mutually in the heating element. The universal heating elements can be used for garments, seat heaters in vehicles, heating pads, heating blankets, etc., which are simple to make.

Risikko and Anttonen tested some personal heating systems using combustion and chemical or electrical energy to study the use of personal heaters in cold work [24]. Table 1 lists the heating systems they evaluated.

TABLE 1. Heaters and Their Target Skin Areas [24]

Heater	Energy	Target Area
Bag filled with solid metal powder, reaction with water	chemical	fingers
Bag filled with solid metal powder, reaction with air	chemical	fingers
Bag filled with saline solution	chemical	fingers
Large heat bag filled with saline solution, belt	chemical	central body
High voltage wired gloves (9.6 V • 0.52 A = 5 W)	electrical	hand/back
Low voltage wire gloves (1.5 V • 0.67 A = 1 W)	electrical	fingers
Low voltage wire socks (1.5 V • 0.67 A = 1 W)	electrical	toes
Charcoal burner, distribution tubes	combustion	central body

The effect of heating on the heated loss of the hand was measured with a hand model in a climatic chamber (T_a = –10 °C, v = 1 m/s). The thermal hand had seven zones in which the surface temperature was kept at 20 °C. The thermal insulation of the referenced glove and mitten was 1.6 m^{2}K/W. It was found that a minimum power of 5–6 W was needed per hand to warm up a human hand efficiently. The warming of the central part of the body

was relatively more efficient due to higher core temperature.

Ducharme, Brajkovic and Frim investigated the effect of indirect and direct hand heating on finger blood flow and dexterity during 3-h cold exposure at –25 °C [25]. Eight healthy male subjects were exposed twice to –25 °C air in a torso heating test where the torso was maintained at 42 °C with an electrically heated vest, while the hands were bare. A hand heating test was used, where the hands were heated with electrically heated gloves. It was found that that the finger blood flow was eight times lower and finger dexterity decreased in the hand heating test compared to the torso heating test despite similar finger temperature.

Brown made a heated glove and placed heating units at the fingertips to provide heat for fingers [26]. A battery was fixed to the wearer's wrist. This glove can be helpful in a cool environment.

Rantanen, Vuorela, Kukkonen, et al. described an implementation of two electrical heating prototypes, which included a sensor shirt for physiological signal measurement [27]. The electrical heating system consisted of 12 conductive woven carbon fabric panels, 9 temperature sensors, 3 humidity sensors, power control electronics, measurement electronics, voltage regulation electronics and batteries. All the electrical devices, excluding batteries, were connected into a polyester shirt. All tests were conducted in an actual winter environment in Finland. The mean skin temperature stabilised or increased somewhat during the heating period except in the case of three test persons who were testing the suit in extreme cold environment from –14 to –20 °C. Consequently, the heating power that was used could not increase the mean skin temperature but could keep the achieved level. In the cold environment the heating power was not adequate for maintaining temperature values.

Zhuang and Zhang studied the heat performance of an electrical heating garment on 18 female students aged 25–35 and found the subjects' comfort temperature at the back side of the waist was between 32.98 and 37.91 °C [28]. Some researchers considered monitoring and measuring biosignals from persons who worked in a low temperature. If the body temperature was lower than normal, the heater in the garment would be turned on automatically to provide heat for the body [29, 30].

Carbon fibre heating elements are popular in EHGs [31]. The carbon fibre heating element has good heat efficiency and can generate heat uniformly and rapidly. The electricity conversion rate can reached 99.9% and each kilowatt-hour of electricity can produce about 6.9 kJ of heat; the surface temperature on the heating element can be discretionarily adjusted according to design; the carbon heating element can generate far infrared radiation with an emissivity rate of 0.95, which has a wave length of 8–15 μm. It can provide the health care function of physiotherapy after extended use. Meanwhile, it can effectively activate the histiocytes inside the human body and promote blood circulation, speed up metabolism and increase immunocompetence [32, 33]. The carbon heating element uses a low voltage DC battery, so it is safe and reliable. The average service life can be up to 100 000 h. Moreover, the heating elements and connection wires can be taken out from the pockets inside the garment before cleaning.

2.1.2. Further improvements for EHGs

Though a carbon fibre heating element has many novel advantages, it is new, it is expensive and it still needs improvement. The real situation is that most EHGs in the market currently use embedded heating wires, which causes several potential problems. Firstly, the heating element is a simple 3D heating pad, which cannot integrate with the human body well and limits the flexibility of the human body; the heating wires are easily broken; the temperature control systems inside EHGs are not well designed and the temperature cannot change smartly according to current necessity in different parts of the body. Secondly, the heating wire cannot produce heat uniformly over a selected area; it produces heat only along the paths where the wires extend; and most importantly, the heat relies on radiation and conduction to the spaces between adjacent wires. Finally, the battery capacity is a significant

problem for those EHGs. The battery used for an electrical heating vest in Holmér, Gao and Wang's experiment lasted for only ~2 h at the highest temperature level [34]. The heating power is also a problem. Rantanen, Impiö, Karinsalo, et al. studied the power consumption of a smart garment in a smart clothing prototype project and found the battery capacity was ~30–40 min of heating [35]. This means heating should be allowed only in an emergency or in situations where it is possible to change or recharge the battery. Consequently, the power sources for an EHG should be further improved to lengthen the heating time for whole clothing systems.

At present, the EHG alone can neither improve thermal protection nor maintain human heat balance in an extreme cold environment (below –14 °C) [21, 26]. In addition, the influence of an EHG on human physiology requires further investigation.

2.2. Phase Change Material (PCM) Garments

Garments can have automatic acclimatising properties if PCMs are used [36]. PCMs are combinations of different types of paraffins, each with different melting and crystallisation points. By changing the proportionate amount of each type of paraffin in the PCM, desired melting and freezing points can be obtained [37]. The most commonly used PCMs on the market are salt hydrates, fatty acids and esters, and various paraffins such as octadecane. PCMs are capable of storing and releasing large amount of energy. Latent heat storage of PCMs can be achieved through solid–solid, solid–liquid, solid–gas and liquid–gas phase change. However, the only phase change used for PCMs is solid–liquid.

2.2.1. Incorporation of PCMs in textiles

PCM changes within a temperature range slightly below and above human skin temperature might be suitable for application in textiles. A fibre, fabric, foam and plastic package with PCMs could store the heat the human body generates, and then release it back to the body. The process

of phase change is dynamic, and the materials continuously change from one state to another due to the level of physical activity of the human body and the ambient temperature. There are three main methods to incorporate PCMs in garments.

- Microencapsuling and spinning: the incorporation of PCMs within a fibre requires that PCMs be microcapsulated. PCMs would be added to liquid polymer, polymer solution, or base material and fibre, and then spun according to conventional methods. The microcapsulated PCM fibres could store heat over a long time. If the ambient temperature drops, the fibre will release heat slowly.

- Coating and laminating: PCMs could be incorporated into the textiles by coating with polymers such as acrylic or polyurethane. To prepare the coating composition, microspheres containing PCMs are wetted and dispersed in a dispersion of a water solution containing a surfactant, a dispersant, an antifoam agent and a polymer mixture. The coating would be then applied to a textile substrate. In an alternative embodiment, an extensible fabric would be coated with an extensible binder containing microencapsulated PCM to form an extensible, coated fabric [38]. PCMs can also be incorporated into a thin polymer film and applied to the inner side of a fabric system by lamination. However, one problem is that PCM coating and lamination may increase the stiffness of fabrics, and the changes in these properties will vary depending upon what percentage of PCMs by weight is used in the fabrics. Another problem is the durability, which needs to be investigated prior to use.

- Packaging: PCMs can be also sealed in small plastic packages, and then put into a garment with many pockets. A normally packaged PCM vest has a large mass, which can store a large amount of heat. Additionally, it is convenient to take out these PCM packages before cleaning the outer garment. Figure 1 illustrates a PCM vest and packaged PCMs [39].

Figure 1. (a) PCM vest and (b) packaged PCM [39]. *Notes.* PCM—phase change material.

2.2.2. Testing PCMs incorporated textiles

The earliest application of PCM incorporated into textiles dates back to 1979. Scientists at the U.S. Triangle Research and Development Corporation were the first to develop and patent the technology for incorporating microcapsulated PCMs inside textile fibres to improve their thermal performance [40].

Currently, PCM garments are studied in a variety of apparel items (e.g., hats, gloves, boots, jackets and vests) as personal cooling equipments; however, investigations seldom focus on PCM heating garments. Pause applied PCMs to the fabrics of nonwoven protective garments and found that their poor thermophysiological wearing comfort property could be improved [41]. The wearing times of nonwoven protective garments can be extended and result in an increased productivity. Ying, Kwok, Li, et al. analysed the physical mechanisms of heat and moisture transfer through textiles incorporating PCMs and found thermal regulating capability of textiles incorporating PCM strongly depended on the amount of PCM [42]. Choi, Chung, Lee, et al. carried out wear trials of PCM garments and investigated the appropriate amounts of PCM to give objective and subjective wear sensations [43]. Rectal, skin and clothing microclimate temperatures, saliva and subjective evaluation measurements were conducted during wear tests. They found that vapour-permeable water-repellent garments with PCM showed a much higher temperature than those without PCM in

a slightly cold environment (5 °C, 65% relative humidity). Wang, Li, Tokura, et al. described a simulation of the physical processes of coupled heat and moisture transfer in a clothing assembly containing PCM [44]. The results showed that PCMs can delay the decrease in temperature of the clothing. Wang, Li, Hu, et al. reported a study on the impact of PCMs on intelligent thermal-protective clothing and found that clothing assemblies with PCMs could save ~30% energy in the temperature control process [45]. Li, Li, Li, et al. studied the physical processes of coupled heat and moisture transfer in porous materials with PCMs and self-heating materials [46]. The results showed that PCMs could be recycled to maintain constant temperature in the fabric longer with self-heating materials.

Gao, Kuklane and Holmér tested three PCM heating vests on a heated thermal manikin at a constant temperature of 30 °C in a subzero environment (air temperature of –4 °C, and air velocity of 0.4 m/s) [47]. Figure 2 illustrates the heating effects of PCM vests on a heated dry thermal manikin. The heating effects lasted for ~3–4 h, and the highest heating effect reduced the torso heat loss by up to 20–30 W/m^2 during the first 2 h. The results also showed that the PCM vest with higher melting/solidifying temperature had a greater and longer heating effect.

Recently, Holmér, Gao and Wang studied the performance of two PCM vests and an electrical heating vest on a 17-zone heated dry thermal manikin (manikin skin temperature was set at 30 °C) at an ambient temperature of 16 °C, 30%
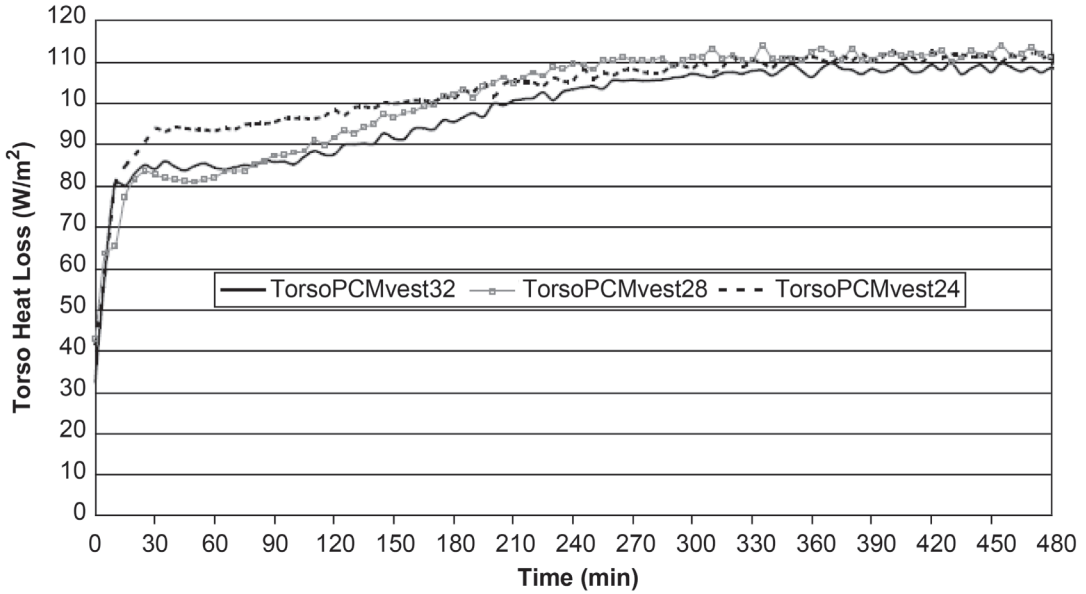
Figure 2. Heating effects of phase change material (PCM) vests (T_{melt} = 32, 28, and 24 °C) on the thermal manikin in the subzero environment [47].
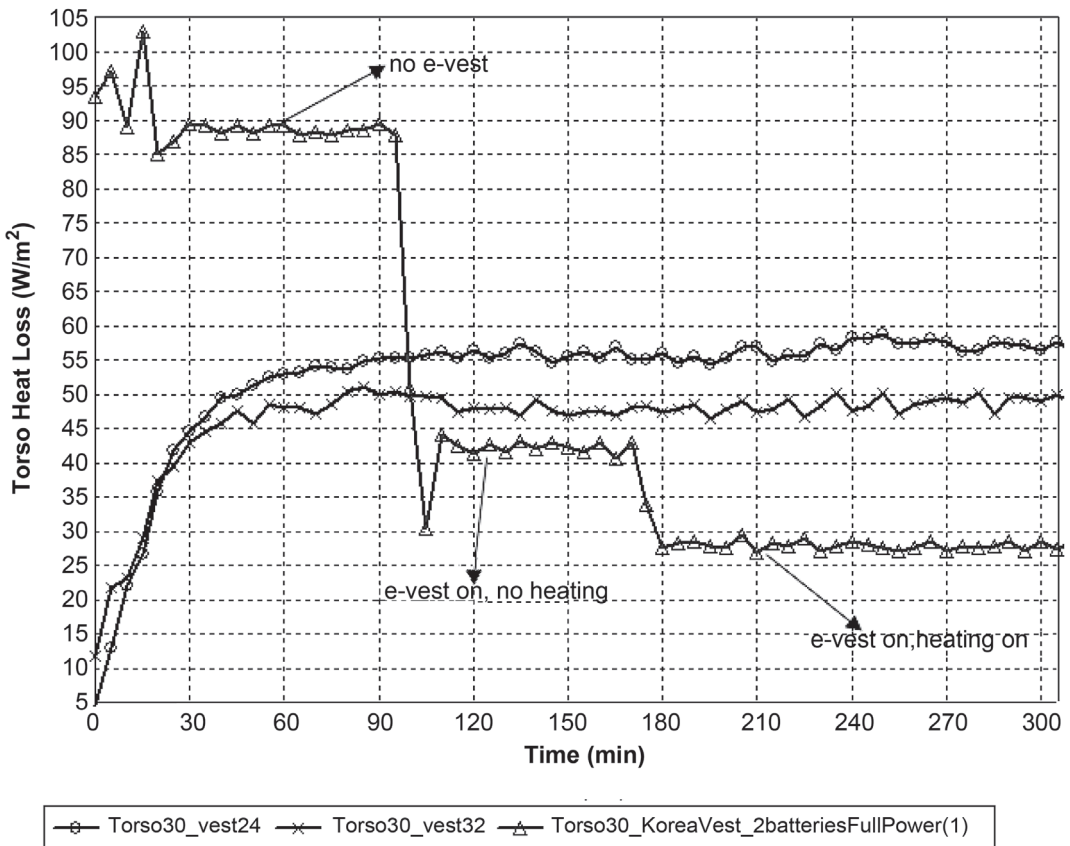
Figure 3. Manikin torso heat losses for phase change material (PCM) vests and electrical heating vest [34]. *Notes.* PCM vests worn over manikin stretch coverall, $T_{manikin}$ = 30 °C, T_a = −4 °C, V_a = 0.4 m/s.

relative humidity and air velocity of 0.4 m/s [34]. Two 2-kg packaged PCM vests were used in the test. They weighed ~2 kg each and had different melting points (24 and 32 °C). An

electrical heating vest was also used; it had 6 carbon heating strips with an electrical resistance of 29 Ω each, and two 7.4-V, 2 200-mAh DC battery power sources. Figure 3 shows the results.

Heat losses from the torso of the thermal manikin for two PCM vests were 55 and 48 W/m^2 respectively, which can be explained by the PCM vest with a melting point of 32 °C having a larger temperature gradient (16 °C) and releasing more heat. The electrical heating vest with full battery power reduced the heat loss to 27.4 W/m^2, which was ~36% compared with only the vest and no heating condition. The maximum heating power in full battery mode was ~11.3 W, which was 41.2% of the total heat loss. The results showed that the heating power used in the tests was theoretically not adequate to maintain the heat balance. To maintain heat balance, a heating power of 27.4 W/m^2 is necessary, which means the power source voltage for this heating vest has to be increased to 18.9 V. It is still a problem whether the carbon heating elements can endure this voltage or not.

2.2.3. Challenges for PCM garments

There is no question PCMs can store heat energy as they change from solid to liquid phase, and release heat when they change from liquid to solid state. However, to bring thermal comfort for the human body in a cold environment, PCMs must release enough heat in the garment layers to reduce heat loss from the human body to the environment. How much heat is released from PCMs greatly depends on the temperature gradient from the skin surface through clothing ensembles to the outer environment and how much PCM is added to the garment. PCMs incorporated in garments by coating, lamination and fibre spinning technology have small heating effect due to their low mass [48, 49, 50, 51]. A packaged PCM garment is heavy and may be only suitable for those people who take part in activities or are exposed where additional weight is not an issue or where gain during exposure overweighs possible performance loss.

On the other hand, not all the PCMs would go through phase changes when a human moves from a warmer environment to a cold environment. PCMs close to the human body may probably remain near skin temperature and stay in a liquid state, while PCMs in the outside layer of clothing have already solidified. Once

PCMs solidify, the heat release process ends and it is necessary for heat sources to reach liquid state to recover their heating function. The factors affecting the effectiveness of a PCM heating garment should be further investigated. In addition, the PCM effect will disappear gradually after PCM incorporated garments have been washed several times. This does not apply to packaged PCM garments.

2.3. Chemical Heating Garments

A chemical heating garment uses a reaction of chemical substances to generate heat, e.g., chemical energy can be turned into heat energy by oxidisation. Chemical heating garments are widely used in diving fields to protect divers in cold water.

2.3.1. Testing chemical heating garments

Gluckstein and Farmington invented a warming suit to provide heat in cold climates for long periods [52]. The comfort suit incorporated provisions for a chemical reaction between the exhaled breath and at least one chemical. Heat released by the reaction warmed the body parts adjacent to the reaction site. The warm gaseous reaction products were distributed to the body extremities which were warmed by sensible heat of the gas by using the pressure of exhalation.

Mayo and Nashau developed a diver suit with a heat source system [53]. The system used a mass of chemical reactants selected to provide a highly exothermic chemical reaction devoid of gaseous by-products. A high heat of fusion material surrounded the mass of reactants and acted as a heat storage unit for dissipating heat at a controlled rate, heat that was obtained from the exothermic reaction. The chemical reaction can be expressed as

$$2B + \frac{3}{2}O_2 \rightarrow B_2O_3 + 1.29 \quad kg \cdot J/mol. \quad (2)$$
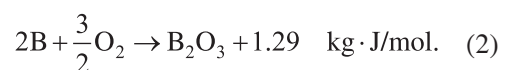
Chan and Burton developed a method for free divers [54]. A granular mixture of magnesium and iron particles packed in 45-mm^2 sachets was used for local heating. The laboratory and sea trials proved that it could provide adequate supplementary heating for shallow water divers
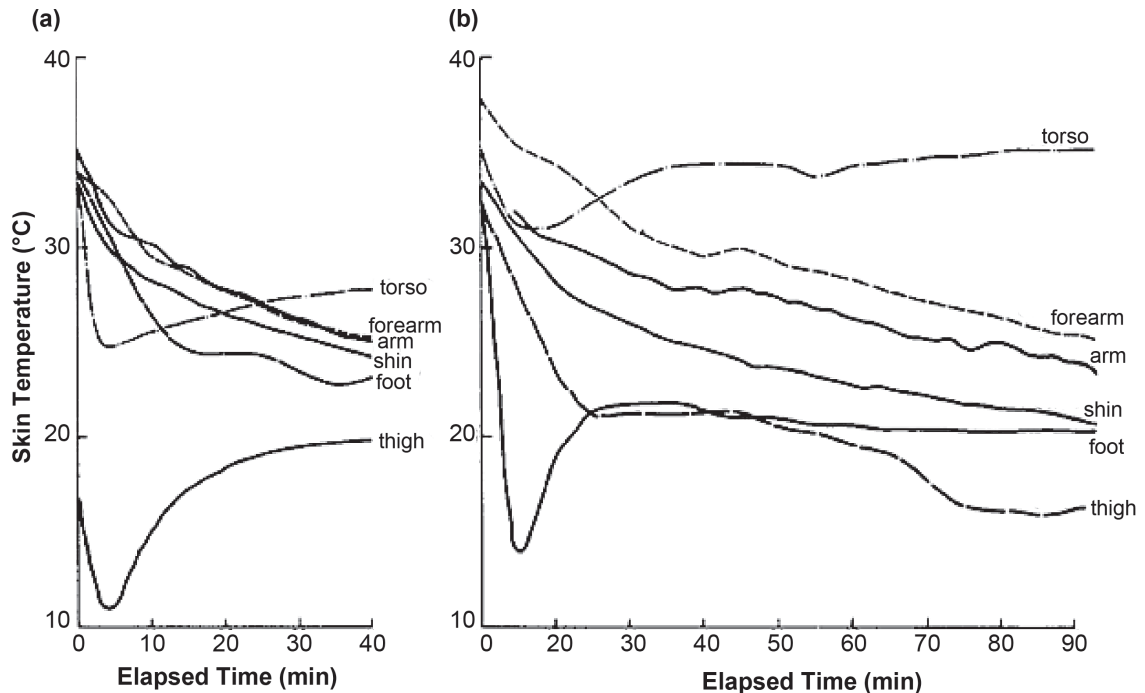
Figure 4. Skin temperatures for (a) unheated and (b) heated dives in 5 °C water [55].

(shallow water may be arbitrarily defined as not deeper than 50 m). Chan and Burton also described the development, testing and performance of the heating sachets [55]. The heating rate and duration of output of the sachets were controlled by particle size and mixture ratio of the constituent magnesium and iron particles. They also presented and discussed results of live tests in different dive situations. Figure 4 illustrates the temperature history at several sites on the skin during the objective performance tests for a 40-min control run and an 83-min heated run in water at 5 °C.

The gloved hands and protected feet were numb at 23 min, whereas shivering was reported at 31 min and the subject terminated the test at 40 min. For the heated run, 30 local heating pads were used in the torso garment and 4 in the gloves to give an estimated power of ~140 W over the first hour. Subjectively, the torso heating was readily acceptable throughout, but the legs and particularly the feet became very cold near the end of the exposure.

Burton used a simple mathematical model of human-stored heat loss to predict voluntary exposure times of unheated divers who became cold and to estimate body heat debt [56]. The model makes it possible to analyse documented dives by a laboratory and by others, including recent exposures in Antarctica using low level supplementary heating.

Simmons, Simmons and Simmons developed a heated vest with pouches for accommodating inserted heating packets [57]. The human torso was heated with an air-activated chemical heating packet. The vest was formed from cloth and was preferably soft and sufficiently supple to conform to the body contours during use. Eckes developed an article of clothing for use with a thermal packet for affecting the heat transfer between the packets; it included a torso enveloping portion conforming to the wearer's body [58]. Hansen invented a hand warming device for use in a jacket or pants pocket [59]. The hand warming package was portable and had controllable heating, which could be connected to clothing, such as gloves, socks, jackets or heating garments and bibs. The heating package allowed the user to carry and conceal it in the jacket or pants pocket and to activate it in the pocket to produce controllable heat for one use.

Currently, body warmer pads are well developed in the world market, especially in Japan [60]. Warmer pads are often made of iron powder, wood powder, activated carbon, inorganic salt and water. Those raw materials can be oxidised in the air and release heat, which can last for ~12 h and their highest temperature may reach to 68 °C. The chemical reaction inside a body warmer pad can be explained with the following chemical equation:

$$Fe + \frac{3}{4}O_2 + \frac{3}{2}H_2O \rightarrow Fe(OH)_3 + 402 \quad kJ/mol. \tag{3}$$
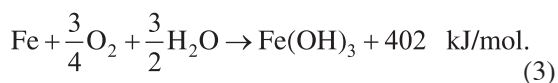
The body warmer pad consists of three layers: raw material, adhesive and nonwoven fabric package layer. The raw material layer is in the nonwoven fabric package and the adhesive layer is used to bond the whole pad on the surface of the garment.

2.3.2. Weak points of chemical heating garments

Chemical heating pads are convenient for consumers and they are cheap; they can be bonded to any part of the human body if necessary. However, their temperature cannot be controlled and it is difficult for the old and for children to judge to which layer of clothing they should be attached. A heating pad attached to underwear in some parts of the human body causes the skin to burn due to the pad's temperature of above 42 °C. Preventing chemical substances inside a heating pad from leaking should also be taken into consideration during the design process. In addition, the physiological reaction of chemical heating garments on the human body should be further investigated.

2.4. Fluid/Air Flow Heating Garments

A fluid/air flow heating garment has a liquid/air circulation tubing system inside the garment; soft tubes or other hollow media are embedded in it. Since water has good heat enthalpy and is nontoxic, it is frequently used in a liquid flow heating garment.

2.4.1. Testing of flow heating garments

Siple developed a body warming jacket which was equipped with one or more warm liquid circulating systems [61]. The jacket was constructed so that a large area of the body could be warmed efficiently. Slack invented a heating garment which incorporated a flow path of a circulating heating liquid for warming swimmers in cold water [62]. A heater and a pump unit were connected to the garment and served to heat the circulating liquid and to cause it to flow from the heater through the garment and back to the heater. The heater used the reaction of water and calcium to produce hot hydrogen gas and slack lime. Hearst and Plum developed a liquid heating protective garment by using a chemical heat source to heat the water flowing in the garment [63]. The objective for this garment was to provide a portable heat exchange device that used the heat created during the transition of a chemical from a liquid to a solid state.

Parker, Mayo and Harvey developed a liquid loop garment which was used to provide thermal protection for the human body in hostile temperature environments [64]. The inlet and outlet manifolds were each connected with a plurality of the channels so that the heat transfer liquid could be passed into an inlet valve and distributed over the body of an individual with sufficient control of temperature variations in the garment. This garment was especially intended as an underwater diver's heating suit to protect divers from extreme cold environments normally encountered at depths.

Wissler outlined a mathematical model of human thermal regulation to simulate various kinds of clothing and active heating devices [65]. In this model, a human body was divided into 15 cylindrical elements representing the head, upper and lower trunk, and proximal, medial and distal segments of each arm and leg (Figure 5). The model was used to analyse the performance of air/liquid warming vests developed to alleviate cold stress in soldiers is a cold environment.

Szczesuil and Masadi developed a body heating garment which used fluid carrying tubes and provided both air and vapour permeability to promote convective heat transfer while also
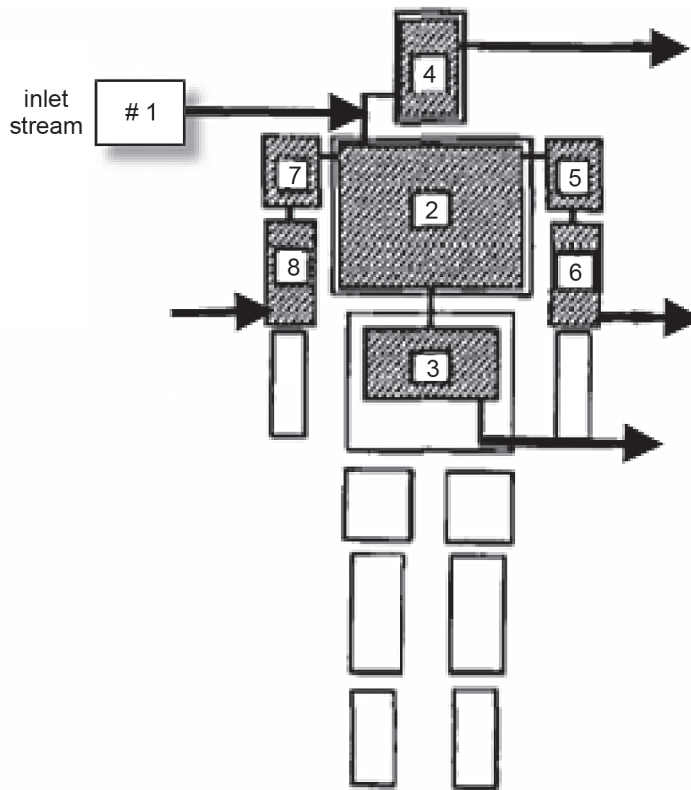
Figure 5. Schematic representation of heat exchanger elements and flow path used to form an air-warming vest [65].

providing conductive heat transfer [66]. The heating garments were made with a bladder sealed at its edges to provide an alternative to sewn-in tubes. Cano developed a personal watercraft garment heating system [67]. It could provide warmth to the wearer of the personal watercraft during a cold winter. The garment had tubing incorporated in the lining of the garment to obtain a comfortable temperature.

Coca, Koscheyev, Dancisak, et al. investigated thermal regimes within a liquid warming garment for body heat balance during exercise [68]. They found that it was possible to stabilise rectal temperature and provide comfort during exercise. A low thermoneutral water temperature of 24 °C in the liquid warming garment before exercise could effectively assists rectal temperature stabilisation.

Koscheyev, Leon and Dancisak developed a thermodynamically efficient garment for heating a human body for medical surgeries [69]. The thermodynamic efficiency was provided in part by targeting the heat exchange capabilities of the garment to specific areas and structures of the human body. The heat exchange garment included heat exchange zones and one or more nonheat exchange zones, where the former were configured to correspond to one or more high density tissue areas of the human body when the garment was worn. The system could be used to exchange heat with adjacent high density tissue areas controlled with a feedback control system. Sensed physiological parameters received by the feedback control system could be used to adjust the characteristics of the heat exchange fluid moving within the heat exchange garment. Koscheyev, Leon, Coca, et al. also described a physiologically-based lighter and a shorter liquid warming garment, which included gloves, for astronauts and for future lunar or Mars missions [70]. The physiologically designed warming gloves with tubing bypass can be used to mitigate hand or finger discomfort and augment heat delivery by blood flow. The augmentation of heat delivery by blood flow could improve lower limb blood circulation and sustain comfort.

Recently, Chambers developed a personal warming garment comprising a carrier formed

in the shape of the garment and a bladder comprising at least two channel segments, wherein the channel segments had a substantially flat configuration so as to improve thermal efficiency [71]. The heating garment was relatively simple and inexpensive, lightweight, comfortable and thermally efficient. Most importantly, this personal warming garment could remain effective regardless of whether the user was standing, sitting or lying down.

Flouris, Westwood, Mekjavic, et al. investigated the effect of body temperature on cold-induced vasodilation (CIVD) by using a liquid conditioning garment (LCG) and military arctic clothing [72]. Ten adults (4 females, 23.8 ± 2.0 years) randomly underwent three 130-min exposures to –20 °C incorporating a 10-min moderate exercise period at the 65th min, while wearing an LCG and military arctic clothing. In the prewarming condition, rectal temperature was increased by 0.5 °C via the LCG before the cold exposure. In the warming condition, the participant regulated the LCG throughout the cold exposure to subjective comfort. In the control condition, the LCG was worn but was not operated either before or during the cold exposure. The results demonstrated that most CIVD occurred during the warming condition when the thermometrically-estimated mean body temperature (T_b) was at its highest. Thus, CIVD was triggered by increased T_b, which supported the hypothesis that CIVD was a thermoregulatory mechanism contributing to heat loss.

An air flow heating garment is frequently used for keeping patients warm during prolonged surgery periods. Former studies showed that a circulating-water heating system transferred more heat than forced air, with the difference resulting largely from posterior heating [68, 73]. Circulating water rewarmed patients 0.4 °C/h faster than forced air [74]. Janicki, Higgins, Stoica, et al. found that body temperature was more consistently maintained at a greater than 36 °C temperature during entire orthotropic liver transplantation period if a liquid flow heating garment was used [75].

2.4.2. Challenges for flow heating garments

It is evident that liquid heating garments have an effective heating effect [74, 76, 77]. However, the tubing system inside the garment will more or less make the garment stiff and limit human activity. The heat transfer qualities of tubing material and wall thickness, tubing diameter, total tubing contact surface with skin and distribution media can greatly influence the heating effect of a fluid/air flow heating garment. There is also a temperature difference between the inlet and the outlet of the tube. The flow patterns (e.g., one-way or loop flow), liquid leakage and garment fit should also be considered during the design process. Currently, liquid/air flow heating garments are widely used and investigated in the medical field. The physiological effects of a liquid/air flow heating garment on the human body in a cold environment also requires investigation in the future. Moreover, the cleaning of such flow heating garments also needs to be well-designed.

3. CONCLUSIONS AND RECOMMENDATIONS

Normal thick-layer protective clothing can reduce workers' risks of getting cold injury when exposed to cold environments. Traditional protective clothing is often bulky and heavy, and can severely limit human movements, dexterity and performance. As a result, traditional protective clothing may be not suitable for those workers who are doing fine work in cold environments.

Currently PHGs have some visible drawbacks, e.g., battery performance cannot meet the requirements of long exposure in cold conditions in EHGs; temperature cannot be controlled in chemical heating pads; released latent heat has little effect on the human body in both microcapsulated and packaged PCM heating garments; and liquid/air flow heating systems limit human activities. Compared with the four types of PHGs described in this overview, EHGs are expected to have a promising future. One of the main challenges is to seek new regenerated

energy sources such as solar energy, wind energy, sound wave power [78], human motion and garment friction energy, and/or using a temperature gradient (Nansulate® Paint [79]) to generate long-lasting supply of electricity for EHGs. Additionally, each set of conditions must be individually evaluated for possible use of PHGs. The heating system analyses should also include such interacting items as thermal stress, cold stress, task duration, external work intensity, heating system reliability, safety, unit portability and also economic considerations.

Finally, the consumer market for PHGs is large [80, 81]. The use of personal heating clothing in cold and hot environments is common in industries throughout most of the world. If future work on light, long-lasting heating power is successful, the market for PHGs will increase significantly.

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Paper II

Evaluation of an Electrically Heated Vest (EHV) Using a Thermal Manikin in Cold Environments

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We studied the heating efficiency of an electrically heated vest (EHV), its relationship to the microclimate temperature distribution in a three-layer clothing ensemble, and the effect of an EHV on the clothing's total thermal insulation by both theoretical analysis and thermal manikin measurements. The heat losses at different ambient conditions and heating states were recorded and the heating efficiency of the EHV was calculated. It was found that the EHV can alter the microclimatic temperature distribution of the three-layer clothing ensemble. The EHV can provide an air temperature of 34°C around the manikin's torso skin. The highest temperature on the outside surface of the EHV was around 38°C, which indicates that it is safe for the consumer. The higher the heating temperature, the lower the heating efficiency obtained. This was due to much more heat being lost to the environment, and hence, the heat gain from the EHV was smaller. The heating efficiency decreased from 55.3% at 0°C to 27.4% at −10°C when the heating power was set at 13 W. We suggest adjusting the heating power to 5 W (step 1) at an ambient temperature of 0°C, while at −10°C using 13 W (step 3) to provide the consumer a thermal comfort condition.

Keywords: cold environment; electrically heated vest; heating efficiency; microclimate temperature; thermal manikin

INTRODUCTION

Protection of the human organism against cold is one of the fundamental functions for protective clothing. Clothing with high thermal insulation is traditionally deemed as a combination of multi-layers of garments, which ensure an appropriate temperature gradient between the human body and the environment. The required thermal insulation of clothing is only obtained owing to heat-insulating properties of particular layers, which are generally referred to as passive type clothing (Wiezlak and Zielinski, 1993). An alternative is the construction of a clothing ensemble serving as an active system, such as clothing with an auxiliary heating system. The most widely available types of heated clothing are electrically heated garments. The heating power of the whole garment and the heating efficiency of the heating element are the two most important parameters to be specially considered during the design process. The heating elements can be metallic heating wires, graphite elements, metallized textile fabrics, electrically conductive rubber, positive temperature coefficient polymers, or a system of water heaters (Scott, 1988). However, the use of such heaters has resulted in many limitations to the garment, such as an increased mass of clothing, increased rigidity of garment, limited human activity, and limited abstraction of sweat as well as vulnerability (Haisman, 1988).

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Recently, a new carbon polymer fabric-heating element designed for heated garments has been successfully developed and launched by the Kolon Glotech Co. Ltd. in Korea (Kolon GloTech Inc, 2008). The carbon polymer-heating element is made up of conductive polymer, which is flexible, easy fitting, and washable. The carbon polymer-heating element can be put into an inner pocket in the back of a garment, and the whole heated garment is intended to be worn as a middle layer in a clothing ensemble (e.g. three or even more layers) in cold environments. The size of the carbon polymer fabric-heating element is $200 \times 250 \times 0.24$ mm and weighs ~ 15 g. A low voltage (7.4 V) rechargeable lithium-ion battery is used as the main power source, which guarantees the safety for the consumer.

This study presents a novel method based on a thermal manikin to evaluate the performance of an electrically heated vest (EHV) in cold environments. A typical three-layer clothing ensemble including the underwear, heated vest and jacket was chosen for the measurements. The effect of an EHV on the microclimate temperature distribution of the three-layer clothing ensemble was also investigated. Moreover, the heating efficiency of the EHV was calculated and analyzed. Finally, some suggestions and further investigations on how to use such an EHV are projected.

METHODS

Clothing ensembles tested

A pair of sports shoes, gloves, long trousers, underwear, vest, and jacket were used for the measurements. Table 1 shows the characteristics and properties of the garments used in the experiments.

The carbon polymer fabric-heating element has a typical four-layer structure, comprised of a protection layer, heat insulation layer, heat generation layer, and base layer (Fig. 1). Three levels of heating power (5, 8 and 13 W) can be selected by the consumers. The total weight of the whole EHV system used in the measurements was 585 g, which is light, slim, and most importantly, does not restrict human activities/movements.

Thermal manikin

In order to measure all heat exchanges, measurements were made using a Newton thermal manikin (MTNW, Seattle, WA, USA), shown in Fig. 2. This manikin has 20 segments for which the surface temperature was controlled independently, and the total heat input required to achieve this was accurately

Table 1. Descriptions of the clothing ensemble

Clothing ensemble	Description
Sports shoes	Light weight Gore-tex with mesh detail, low-density butyl outsole
Trousers	Polyester, size M
Underwear	Shirt: long sleeve coolmax
	Underpants: pure cotton
Electrically heated vest	Polyester vest with 100% nylon batting
Gloves	Pure cotton, knit gloves
Jacket	Gore-tex with 100% nylon lining

measured. This heat input is a direct measure of the heat loss from the manikin. The skin surface temperature and heat loss of each zone were obtained directly from MTNW's ThermDAC software. The whole manikin system was placed in a controllable climatic chamber, where various environments can be simulated.

With this manikin, the clothing total thermal insulation was calculated by the parallel method and the serial method (EN 342, 2004 and EN ISO 15831, 2004). The parallel method (e.g. Huang, 2007) sums up the heat losses of all 20 segments, area-weighted skin temperatures, and body segment areas to obtain the total insulation, which is given by:

$$R_{tp} = \frac{\left[\left(\sum_{i=1}^{20} \frac{A_i}{A} \times T_{ski}\right) - T_a\right]A}{0.155 \times \sum_{i=1}^{20} H_i}, \qquad (1)$$

where R_{tp} is the total thermal insulation of the clothing ensemble, clo; A_i is the surface area of the segment i and A is the total surface area of the thermal manikin, m²; T_{ski} is the local surface temperature of the segment i of the manikin and T_a is the air temperature, °C; H_i is the local heat loss of the segment i of the manikin, W.

The second method (i.e. the serial method) calculates the local thermal insulation first and the local insulation is averaged in terms of surface area, which can be expressed as (e.g. Anttonen, 2001)

$$R_{ts} = \sum_{i=1}^{20} \frac{A_i}{A} \times \left[\frac{(T_{ski} - T_a) \times A_i}{0.155 \times H_i}\right], \qquad (2)$$

where R_{ts} is the total thermal insulation of clothing ensemble calculated by the serial method, clo.

Test procedures

The skin surface temperature of the thermal manikin was set at 33°C to simulate the skin temperature
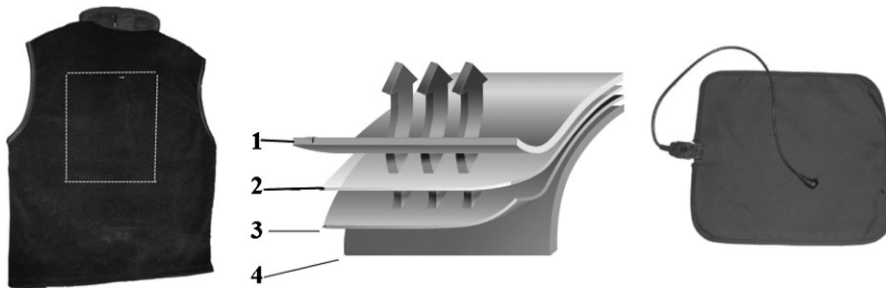
Fig. 1. The EHV and four-layer structure of the carbon polymer-heating element: (1) protection layer; (2) heat-insulating layer; (3) heat generating layer; and (4) base layer.
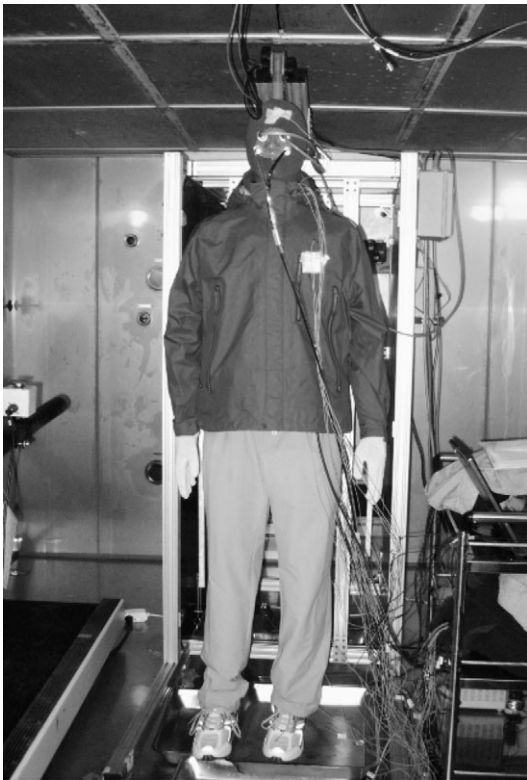

Fig. 2. The Newton thermal manikin in the climatic chamber.

of the human body in comfortable conditions (Yoo and Kim, 2008). Sixteen point temperature sensors were used to measure the microclimate temperatures of the three-layer clothing ensemble. Half of them were adhered by surgical tape (3M^{TM} Micropore^{TM}) to the chest and back sites of the clothing outer layer to measure the clothing surface temperature. Other temperature sensors were placed between each adjacent layer (e.g. between the thermal manikin skin and underwear layer) to measure the temperature

of the microclimate within clothing. The air layer temperatures surrounding the outside of clothing ensembles were also measured (sensors were placed 2 cm away from the outer surface of the jacket). The temperature data were collected and recorded every minute through two 8-channel Technox LT-8A data logging systems (Technox Inc., Korea). For the EHV, two heating levels were chosen for the measurements: step 1 (5 W) and step 3 (13 W). For the ambient conditions, two temperature levels were chosen: 0°C (cold) and −10°C (very cold). The relative humidity was controlled to 30 ± 5% and the air velocity in the climatic chamber was set to 0.4 ± 0.1 m/s.

RESULTS AND DISCUSSION

Clothing thermal insulation

Figure 3 shows the total thermal insulations of the three-layer clothing ensemble calculated by equation (1) (the parallel method) and equation (2) (the serial method). The thermal insulations calculated by equation (1) are stable and repeatable in both of the environmental conditions. However, the values calculated by equation (2) when the heating power is on (5 W in step 1, 13 W in step 3) show significant differences compared with values of the whole clothing ensemble without heating power, especially when the heating power is set at 13 W in step 3. This is because the EHV changes the evenness of the thermal insulation distribution of the whole system. It has already been demonstrated that the serial method overestimates the effect of the actual insulation when measured on a thermal manikin with homogenous surface temperature distribution (Kuklane et al., 2007). Thus, manufacturers should provide the consumer with thermal insulation values calculated by the parallel method rather than by the serial method. The temperatures measured on the back under the EHV should also be indicated for each heating
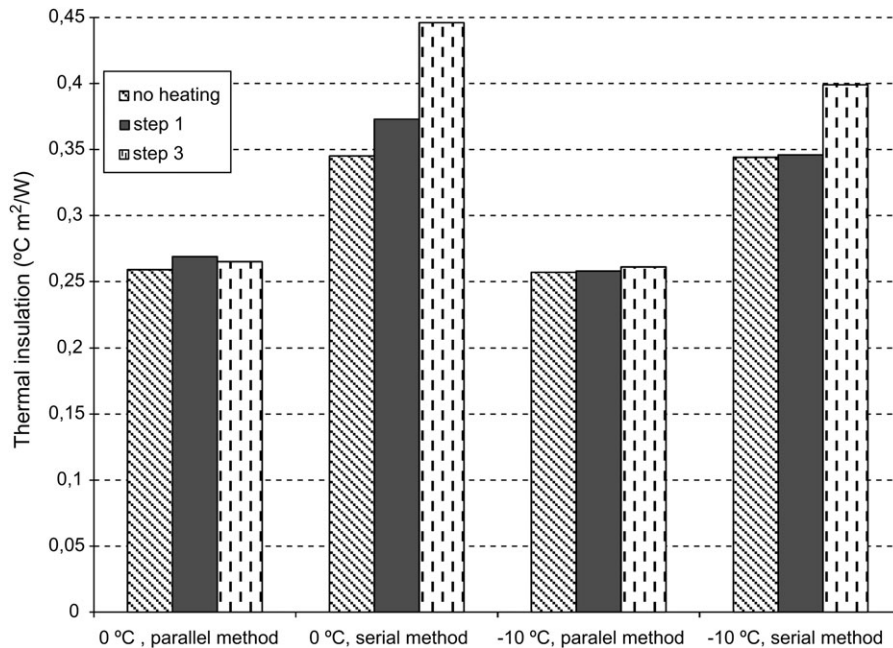
Fig. 3. Clothing total thermal insulations at different heating states, 0 and −10°C.

power to provide consumers with reference values to prevent pain or skin burns when wearing the EHV.

Effects of heating power on microclimate temperature distribution

Figure 4a shows the measured microclimate temperatures of the three-layer clothing ensemble for the entire test period at 0°C when the heating power was turned off and Fig. 4b when the heating power was 13 W. In Fig. 4b, the abrupt changes on the curves approximately every 2 h are due to changes in the power supply (the duration of heating for each battery is about 2 h at step 3). Compared with no heating, the EHV with heating power greatly increased both the temperatures on the surface of the vest and between the vest and jacket by up to 10°C. The temperature between the skin and underwear also increased by ∼4°C. However, there was no significant change of temperatures on the underwear and between the underwear and vest. This is explained by the fact that heat fluxes are apt to move in the direction of the outside of the clothing because the low temperature there causes a larger temperature gradient in that direction. The temperature on the back site of the EHV at its highest heating power (step 3) was ∼38°C, indicating that it is safe for human skin.

Similarly, Fig. 4c shows the microclimate temperatures of the three-layer clothing ensemble for the entire test period at −10°C when the heating power was turned off and Fig. 4d when the heating was 13 W. The abrupt changes on the curves in Fig. 4d are also attributed to changes in the batteries during the test period. The temperatures on the surface of the vest, between the vest and jacket, and between the skin and underwear increased by ∼4 to 12°C compared with no heating. The highest temperature on the back site of the EHV at step 3 was still ∼38°C. However, the mean temperature on the outer layer surface of the EHV decreased by 5°C compared with that of 0°C in Fig. 4b. The average microclimate air layer temperature between the skin and underwear was still ∼34°C, which indicates that the EHV can provide a comfort condition for the consumers even at −10°C.

Figure 5a shows the temperature distributions across the three-layer clothing ensemble at the temperatures of 0° and Fig. 5b at −10°C. It can be easily seen that the measured air layer temperature between the skin and underwear is higher than the skin surface temperature. The EHV changed the microclimate temperature distributions for both of the heating powers (5 and 13 W). The air layer temperature next to the skin was ∼34°C, which proves that the EHV can put human skin in a thermal comfort condition. The average outer surface temperature of the EHV at a heating power of 13 W increased by 12°C compared with that of no heating power at 0°C (Fig. 5a). For an ambient temperature of
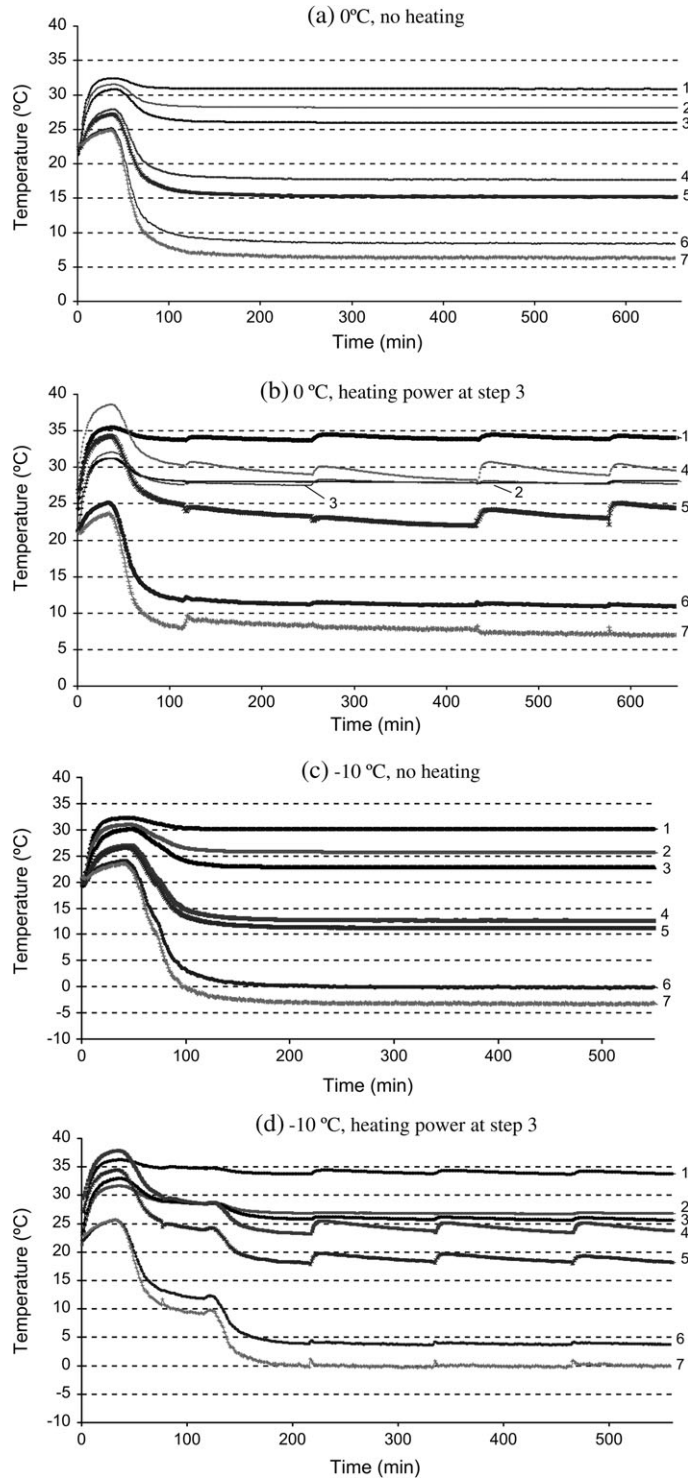
Fig. 4. The microclimatic temperature distribution of a three-layer clothing ensemble at 0 and $-10°C$. All values showed here are averaged temperatures measured from the chest and back sites of the clothing outer surface: (1) between skin and underwear; (2) on the underwear; (3) between the underwear and vest; (4) on the vest; (5) between the vest and jacket; (6) on the jacket; and (7) 2 cm away from the jacket; (a) 0°C, no heating, (b) 0°C, heating power at step 3, (c) $-10°C$, no heating, and (d) $-10°C$, heating power at step 3.
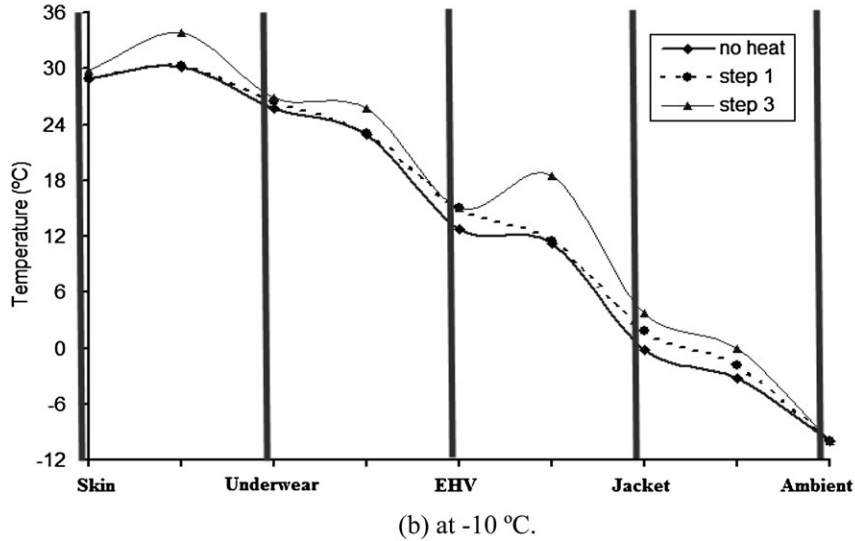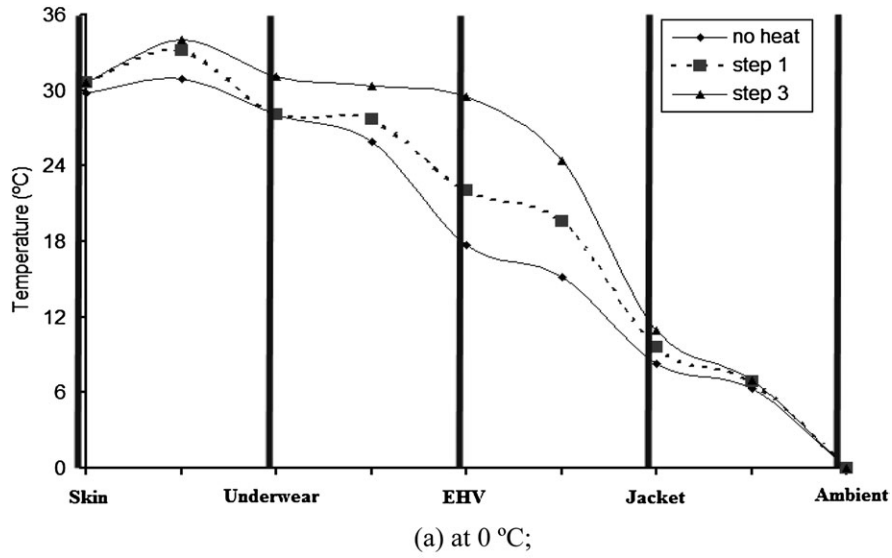
(a) at 0 °C;

(b) at -10 °C.

Fig. 5. The microclimate temperature distributions at stable states. All values are averaged temperatures obtained from the chest and back sites of the clothing outer surface (a) at 0°C and (b) at −10°C.

0°C, the heating power at 5 W is enough to keep the torso of the consumer in thermal comfort. However, such a heating power (5 W) for the EHV at −10°C cannot keep the torso of the manikin in a thermal comfort condition. As a result, the heating power of the EHV should be set in step 3 at −10°C to generate sufficient heat for the consumer to achieve a thermal comfort condition.

Heating efficiency

All heat losses from the Newton thermal manikin in different environmental conditions and heating states can be directly obtained from the ThermDAC recording system. The heating output power of the EHV can be calculated from the capacity of the battery and the heating conversion rate of the heating elements. The heating efficiency of an EHV is defined as:

$$\eta = \frac{HL_{area}}{P_{batt}k} = \frac{\sum_{i=1}^{n} H_i A_i}{P_{batt}k}, \qquad (3)$$

where HL_{area} is the decrease in the area-weighted heat loss (in watts) from the torso of the manikin

when the EHV is switched on, compared with when it is switched off. As explained above, the heat loss from the manikin is measured as the power that must be used to maintain the manikin's temperature. Four of the manikin's segments are on the torso, chest, shoulders, stomach, and back. H_i is the decrease in the amount of heat that goes to the segment i (watts per meter square); A_i is the surface area of the segment i (m^2); P_{batt} is the output power of the battery (W); k is the energy conversion rate of the heating element (%), here for the carbon polymer fabric-heating element used in the experiment. The conversion rate was set at 90%.

The heating efficiencies of the EHV at different heating states and environmental conditions are listed in Table 2. As expected, ambient temperature affects heating efficiency. Much more heat is lost to the environment, making the heating efficiencies at $-10°C$ much lower than at $0°C$. The heating efficiency of the EHV with a heating power in step 1 of $0°C$ is higher than that of step 3 at the same heating power. This is explained by more heat being lost to the environment due to a higher temperature gradient when the heating power is at step 3 (i.e. 13 W). The heating efficiency at Step 1 at $0°C$ is higher than at Step 3, whereas at $-10°C$ it is lower. This latter condition is probably caused by the fact that the temperature gradient between the vest and the ambient at $0°C$ is 5°C higher than that at $-10°C$. Although this EHV can generate a comfortable microclimate condition for the consumer, the heating efficiency should still be further improved to save energy. Some feasible approaches such as the development of a new heating element with even higher heating conversion rates (up to 99%) might be considered in the future.

Moreover, understanding the knowledge of the heating efficiency of a personal heating system (PHS) such as an EHV serves the following three main purposes (Xu et al., 2006): (i) information of the heating efficiency equation can be used to analyze the body heat balance by estimating the heat gain from a PHS in physiological studies; (ii) the heating efficiency relationship can be used to im-

prove mathematical simulations of human responses with a PHS; and (iii) the knowledge of heating efficiency may help designers convert physiological heating requirements into the requirements of improving the performance of a PHS.

In this study, measurements were only conducted in two different environmental conditions with the same air velocity (0.4 ± 0.1 m/s) and clothing combination. The addition of other air velocities and clothing combinations could significantly affect the heating efficiency of an EHV. Further tests and theoretical analysis would be required to investigate how these parameters might affect heating efficiency. In addition, future comparisons between thermal manikin tests and human subject tests on the performance of an EHV would be useful.

CONCLUSIONS

This study used a novel thermal manikin to evaluate the performance of an EHV in combination with a typical three-layer clothing ensemble. The total thermal insulations calculated by the parallel method and the serial method show that the EHV can alter the thermal insulation evenness of the whole clothing ensemble. As a result, the thermal insulation values calculated by the serial method are much higher than those by the parallel method. When the EHV is worn as a middle layer in a three-layer clothing ensemble, it effectively provides a comfortable air temperature around the torso of the manikin skin. The heating efficiency of the EHV decreases greatly with the decreasing ambient temperature. The heating efficiency should be further improved to save energy and to provide a longer time of optimal microclimate for the human body. We suggest that the heating power in step 1 (5 W) be used at an air temperature ~$0°C$ and in step 3 (13 W) at an air temperature below $-10°C$.

Table 2. The heating efficiencies of the EHV at two ambient temperatures

Ambient air temperature (°C)	Heating efficiency of the EHV (%)	
	Step 1 (heating power: 5 W)	Step 3 (heating power: 13 W)
0	79.6	55.3
−10	4.7	27.4

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Paper III

Effects of Air Velocity and Clothing Combination on Heating Efficiency of an Electrically Heated Vest (EHV): A Pilot Study

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Cold endangers the heat balance of the human body. Protective clothing is the natural and most common equipment against cold stress. However, clothing for cold protection may be bulky and heavy, affecting human performance and increasing the work load. In such cases, a heated garment with built-in heating elements may be helpful. This pilot study presents a method based on a thermal manikin to investigate the effects of air velocity and clothing combination on the heating efficiency of an electrically heated vest (EHV). An infrared thermal camera was used to detect surface temperature distributions of the EHV on the front and back. Results show that the heating efficiency of the EHV decreases with increasing air velocity. Changes in EHV sequence in the three-layer clothing combination also significantly affect the heating efficiency: it increases with the increasing number of layers on top of the EHV. The highest mean temperature on the inner surface of the EHV was 40.2°C, which indicates that it is safe for the wearers. For the EHV to heat the human body effectively, we suggest that it be worn as a middle layer. Finally, the EHV is especially suitable for occupational groups whose metabolic rate is below 1.9 Mets.

Keywords   air velocity, clothing combination, cold environment, electrically heated vest (EHV), heating efficiency, infrared thermography

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INTRODUCTION

The hazardous effects of cold on the human body can include dehydration, numbness, shivering, frostbite, immersion foot, and hypothermia.[1,2] If the cold protection is insufficient, the body temperature will decrease, starting with peripheral parts of the body and gradually progressing to deep body tissues and the body core.[3] When the body core temperature drops below 35.0°C, it is defined as hypothermia. To maintain the human core body temperature in a narrow range around 37.0°C, external protection is needed. Protective clothing is one of the natural and most common types of equipment against cold stress. The performance requirements of protective garments often include the balance of many properties, such as thermal insulation, evaporative resistance, and water vapor permeability.[4]

Clothing is a thermal and moisture barrier between the human body and the environment.[5] The cold protective clothing currently available can be divided into two categories: ordinary clothing and smart clothing. Ordinary clothing is the traditional, thick multi-layer garments including footwear, gloves, and hat. Such a protective clothing ensemble serves the purpose of reducing the effects of cold stress factors. However, the increased weight and bulk of the clothing ensemble may limit human body activity and finger dexterity, reduce human performance, and increase work load and muscular strain.[2,6]

An electrically heated garment (EHG) is one of the most typically worn smart clothing. The EHG uses built-in heating units to generate heat. The built-in heating elements can be flexible electrical element wires, graphite elements, electrically conductive rubber, textile fabrics treated in metallic salt solutions, polyethylene mixed with carbon black, or printed circuit heaters.[7,8] However, these heating elements may constrain human activity to some extent. Recently, a new carbon polymer heating element made from biothermal carbon fibers was launched on the market. They are slim, light, and washable, and most important, there is no limit to human movement.[9]

One of the earliest applications of electrically heated clothing goes back to World War II.[10] Bomber aircrews were equipped with electrically heated gloves to alleviate high-altitude frostbite. Since then, electrically heated clothing has been used in many ways, such as by missile fuel handlers[11] and maintenance personnel in the Arctic.[12] However, Burton et al.[13] argued that it is more important to supply heat to the torso than to the extremities. Recent studies have been carried out on the auxiliary heating of gloves to increase finger dexterity, and heated shirts for cold weather protection.[14–16] Those studies revealed that (1) heating efficiency (the ratio of the amount of heat benefit (i.e., area-weighted heat loss decreased from the manikin torso when power supply is turned on, compared with when it is turned off) from heated clothing to total heat input) and (2) heating power (the heat input in

watts) are the two most important parameters to be considered during the design process.

A more recent study[9] has demonstrated that the environmental temperature can greatly influence the heating efficiency of a heated vest. Until now, no data have been published on other factors, such as air velocity and clothing combinations, that may affect the heating efficiency of heated garments.

In this study, we investigated the effects of air velocity and clothing combination on the heating efficiency of an electrically heated vest (EHV) in a cold environment using a thermal manikin. Gagge et al.[17] found that the air velocity linearly increases the convective heat loss from the human body in the range of air velocity from 0 to 0.51 m/s (100 feet per min).

Parsons et al.[18] investigated the effects of wind and human movement on the heat and mass transfer of clothing. They concluded that the clothing thermal insulation reduces heat loss between the body and the environment. Based on these findings, we hypothesized that the changes in air velocity and EHV sequence in a typical three-layer clothing ensemble influence the heating efficiency of the EHV on the manikin. An infrared thermal camera was used to detect the heat source generation from the EHV. The experimental results from the manikin tests were statistically analyzed, and some suggestions on how to improve the heating efficiency of heated garments are summarized. Finally, further studies on how to examine the performance of the EHV are discussed.

METHODS

Clothing Combinations and the EHV

To investigate the effect of clothing combinations on the heating efficiency of the EHV, a typical three-layer clothing ensemble was selected for all the manikin measurements. A pair of military uniforms (code: M), a pair of cotton knit underwear (code: U), an EHV (code: E), a pair of thick polyamide stockings, a pair of sports shoes, and a pair of thick gloves were used in the tests. The details of these garments are described in Table I. Three clothing combinations were chosen: for example, E+U+M, U+E+M, and U+M+E E+U+M stands for clothing E worn as an inner layer, U as a middle layer, and M as the outer layer. EHV was thus worn as an inner, a middle, and an outer layer in the three combinations, respectively.

Six strips of carbon polymer heating elements made from the ultrathin, biothermal carbon fiber were inserted into six separate front and back sacks inside a polyester woven vest. The heating element strips were 155×52×0.82 mm (length×width×thickness), and weighed 16 g. The total heating area accounted for about 8.5% of the total torso surface area. However, there was not enough room to place more carbon polymer elements in the front side of the EHV because of a middle zipper, so only two elements were placed in the front. The remaining four heating elements were placed at the back. A DC power supply box (Xantrex PBX4160-5, Xantrex Technology Inc., Vancouver, Canada) was used as the

TABLE I. Clothing Ensembles

Clothing Ensemble	Description
Knit underwear	Weight: 624 g Material: cotton $I_{cl} = 0.61$ clo
EHV	Weight: 514 g Material: polyester/spandex $I_{cl} = 0.41$ clo (without heating power) $I_{cl} = 0.43$ clo (with heating power)
Military uniform	Weight : 1854 g Material: polyamide/cotton $I_{cl} = 1.08$ clo

Notes: I_{cl}, clothing intrinsic thermal insulation. All clothing thermal insulation values are calculated based on the parallel method according to ISO 15831[19] (2004), i.e., surface area averaged thermal insulation.

main power supply for this EHV. The heating voltage of the power supply can be controlled within ±0.02%. The LCD of the power box displays both voltage and current to two decimal places.

Thermal Manikin

A standing thermal manikin made of plastic foam with a metal frame inside to support body parts and joints was used in the tests.[20] Its height is 170 cm, chest and waist circumferences are 94 and 88 cm, respectively, with a total heated body area of 1.774 m^2. The manikin weighs 33 kg. This manikin has 17 segments for which the surface temperature was controlled independently, and the total heat input required to achieve this was accurately measured. The manikin skin surface temperature was continuously recorded by a special system program (developed by Håkan O. Nilsson).[21] The entire thermal manikin system was placed in a climatic chamber, where various environmental conditions could be simulated.

Test Procedures

The thermal manikin surface temperature was set at 34.0°C to simulate the human body in a comfortable thermoneutral condition.[22] All manikin tests were conducted at an air temperature of 4.5 ± 0.5°C and the relative humidity was 85 ± 5%. For the air velocity, three levels were chosen: 0.22, 0.44, and 0.66 m/s. These values were selected based on the limited self-control range of the climatic chamber (range: 0–0.66 m/s). Air velocity was measured by an anemometer (Swema 3000; Farsta, Sweden) for 3 min, and a mean value was presented. Air inlets in the climatic chamber are from the mesh ceiling, and air outlets are through the lower mesh part of one side wall. The thermographs were taken by an infrared thermal camera (FLIR T200; FLIR Systems Inc., Danderyd, Sweden) to detect the outer surface temperature of the EHV in steady-state during the test period.

For the clothing combination E+U+M, thermogram images were taken immediately after removal of the underwear and military jacket. Inner surface temperatures on the EHV in clothing combination E+U+M were measured by three-point thermocouples (Testo 177-T4 Data Logger; Testo AG, Lenzkirch, Germany, resolution: $0.1°C$). The mean inner surface temperature on the EHV can be calculated accordingly.

Since all the heating elements are located next to the torso of the manikin, we focused on the efficiency of heating the manikin torso. The area-weighted torso heat losses from the manikin in different environmental conditions and clothing combinations can be obtained directly from the test report system. The heating output power for the EHV can be calculated from the heating voltage and the electric current to the EHV. Then, the heating efficiency, (η), of the EHV is defined as[9]

$$\eta = \frac{HL_{area}}{p_{box}} = \frac{\sum_{i=1}^{n} H_i A_i}{p_{box}} \qquad \textbf{(1)}$$

where HL_{area} is the decrease in the area-weighted heat loss (in watts) from the torso of the thermal manikin when the EHV is switched on, compared with when it is switched off. As explained above, the heat loss from the manikin is measured as the power that must be used to maintain the manikin's constant temperature. Four of the manikin's segments are on the torso: chest, back, stomach, and buttocks. H_i is the decrease in the amount of heat that goes to the segment, $i (W/m^2)$; A_i is the surface area of the segment, $i (m^2)$; and P_{box} is the output power of the power supply box (W).
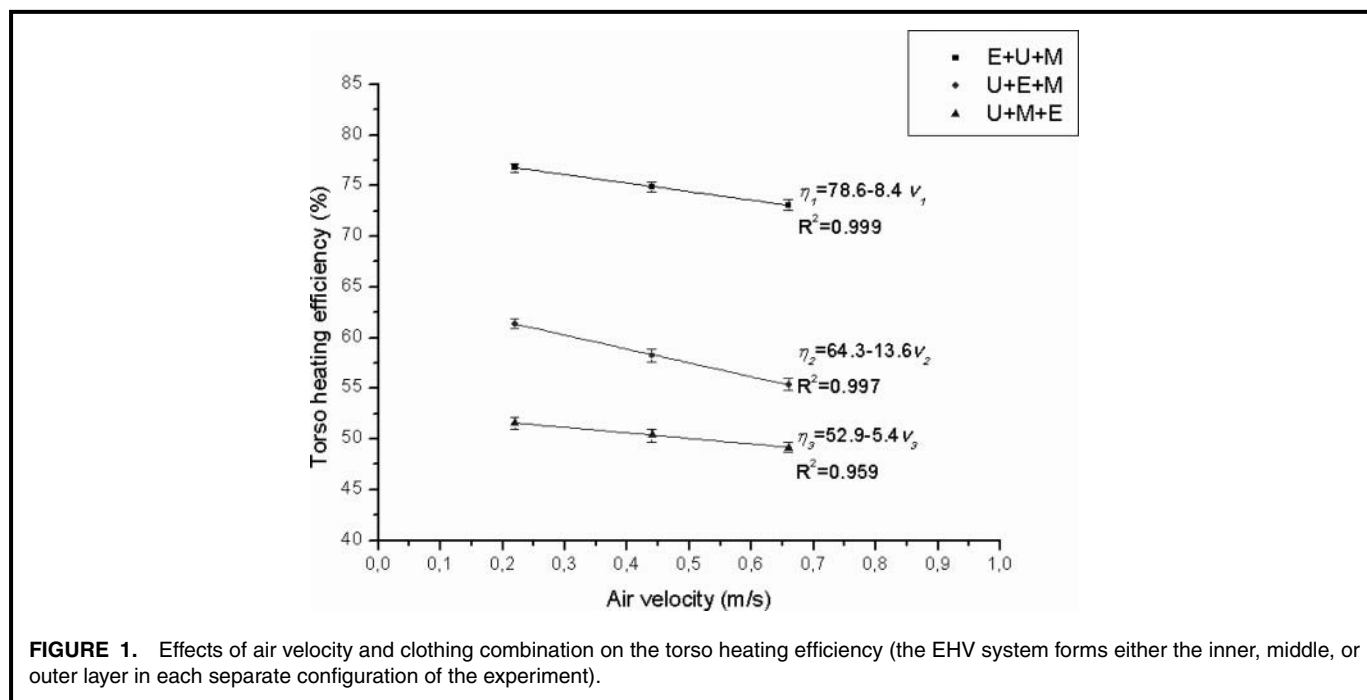
Statistical Analysis

The manikin tests were repeated twice for each clothing combination at three different air velocities. The data from these runs were treated as replicates and averaged. A two-way analysis of variance (ANOVA) was used for statistical analysis (SPSS v. 16.0, Chicago, Ill.) to determine whether the air velocity and clothing combination have significant effects on the heating efficiency of the EHV. The statistical significance level was set at $P < 0.05$.

RESULTS AND DISCUSSION

An electric current of 1.45 A was observed from the power supply box. Combined with the heating voltage of 9.0 V, the heating power of the EHV was 13.05 W, accordingly. The calculated heating efficiencies of the EHV in three clothing combinations at different air velocities are shown in Figure 1. The regression curves for each test clothing combination are also shown.

It can now be seen that the heating efficiency of the EHV in three different clothing combinations decreases with increasing air velocity within the tested, short air velocity intervals. Maximal heating efficiencies in the three clothing combinations at 0.22 m/s were 0.9 to 6.0% greater than the values obtained at two other air speeds: 0.44 or 0.66 m/s. The explanation for this is that greater air velocity results in more heat from the EHV dissipating to the environment. Figure 1 shows that air velocity has the greatest influence on the heating efficiency of the EHV in clothing combination U+E+M, and the least in U+M+E. This is because the M clothing is loose and allows more air ventilation through both sides of the EHV

FIGURE 1. Effects of air velocity and clothing combination on the torso heating efficiency (the EHV system forms either the inner, middle, or outer layer in each separate configuration of the experiment).

in the U+E+M, while the EHV in the U+M+E combination is tighter fitting to U and M: the air can only go through the outer surface of the EHV. Hence, there should be more clothing layers on top of the EHV, and all clothing openings should be closed to gain sufficient heating benefit from the EHV in strong wind.

The results of the two-way ANOVA showed that both the air velocity ($F = 120.69$, $P = 0.000$, partial eta squared $= 0.964$) and clothing combination ($F = 4747$, $P = 0.000$, partial eta squared $= 0.999$) have significant direct influences on the heating efficiency of the EHV. The two-way interaction effect is also statistically significant ($F = 13.47$, $P = 0.001$, partial eta squared $= 0.857$). Thus, it can be concluded that the difference in heating efficiency of the EHV at low air velocity and high air velocity is large. Similarly, the difference in heating efficiency among these three clothing combinations is also large.

According to the regression equations presented in Figure 1, the calculated maximum theoretical heating efficiencies of the EHV in clothing combinations E+U+M, U+E+M and U+M+E (assuming the air velocity is 0 m/s) were 78.6, 64.3, and 52.9%, respectively. It can also be seen from Figure 1 that the EHV has the highest heating efficiency when it served as an inner layer in the three-layer clothing ensemble. On the other hand, the EHV has the lowest heating efficiency when it served as an outer layer. This is because the outer layers on top of the EHV provide an efficient thermal insulation to avoid the loss of too much heat from the EHV to the environment.

Infrared Thermography

The thermogram images were analyzed by the Researcher Program (FLIR Systems). For thermogram images of the EHV in the clothing combination E+U+M at 0.22 m/s, the highest temperatures at the front side of the EHV outer surface above two heating element strips were 24.0 and 26.5°C, respectively. Similarly, the highest temperatures above the three heating elements at the back side of the EHV were 26.6, 24.9 and 26.6°C, respectively. The temperature of the region without heating elements was much lower; for instance, a point temperature on the upper back was 13.8°C, and the temperature on the front area of the EHV was 12.4°C.

The outer two layers (U and M) in the clothing combination E+U+M provided an additional thermal insulation of 1.41 clo (1 clo = 0.155 m²°C/W) to the EHV. In addition, the observed mean inner surface temperature of the EHV in the clothing combination E+U+M at 0.22 m/s was the highest of all test conditions: 40.2°C. Greenhalgh et al.[23] conducted an oximeter safety study to investigate the temperature threshold for human skin burn injuries. They found that the pulse oximeter probes are safe up to a temperature of 43°C for at least 8 hr in well-perfused skin. The highest fabric surface temperature observed in this study is below this value. Therefore, the EHV is safe for wearers.

The $IREQ_{neutral}$ index (clothing insulation required in the specific environmental conditions to maintain the human body in a thermal neutral state) was used to determine the suitable occupational groups for wearing such an EHV in a three-layer clothing ensemble at an environmental temperature of 4.5°C.[24] For a person in clothing ensemble E+U+M at 0.66 m/s ($IREQ_{neutral}$ equals the intrinsic thermal insulation of clothing combination E+U+M: 1.71 clo), the required metabolic energy production to keep thermal neutral was 108 W/m², i.e., 1.9 Mets (1 Met = 58 W/m²). Thus, this EHV is especially suitable for the wearers whose metabolic rate is below 1.9 Mets, such as workers sitting in an office without room heating facilities and occupational workers who carry out light activities, such as hand work (small bench tools, inspection, assembling, or sorting of light materials) and arm work (driving vehicles, operating foot switches, light strolling, etc.).[25] For the occupational groups whose metabolic production is above 1.9 Mets at 4.5°C, the human body can produce enough heat to keep the body thermal neutral. Hence, it is not necessary to use such an EHV. On the contrary, some outer layers might be removed to keep the body in a thermal neutral condition during moderate to heavy activities.

In this study, all thermal manikin measurements were conducted under the constant skin temperature mode at a steady-state. However, this differs with actual use conditions. The human physiological responses to such smart clothing as an EHV are even more important in the transient state. Further studies should be performed on a thermal manikin in physiology mode (i.e., the manikin is in a constant power mode). The measured changes of the surface of the manikin may reflect real changes in skin temperature of the wearers. Finally, human subject trials are required to validate the performances of the EHV. The same clothing configuration and environmental conditions can be used in human subject studies. The metabolic rate of human subjects can be kept at 1.9 Mets (for example, assembly work). Torso skin, mean skin, and core temperature changes and thermal sensation recorded on human subjects can be related to changes in heat loss and heating efficiency measured on the manikin. The condition in which the highest heating efficiency was obtained on the manikin is also expected to have the highest torso skin temperature in human subject tests.

CONCLUSIONS

This study presents a method based on a thermal manikin to investigate the effects of air velocities and clothing combinations on the heating efficiency of an EHV in a cold environment. Results show that the heating efficiency of the EHV decreases with increasing air velocity. Changes in EHV sequence in the three-layer clothing ensemble can also significantly influence heating efficiency. We also found that the EHV has the highest heating efficiency when it served as the inner layer in the three-layer clothing ensemble. However, this EHV might not be suitable worn as an inner layer because the woven vest might affect the wearing comfort. Moreover, the initial intention of making these EHVs was to protect the

human upper body by wearing them as an additional garment over underwear or under a jacket. Thus, we recommended that the EHV be worn as a middle layer to gain sufficient thermal benefit. Finally, we suggest wearing additional layers over the EHV and closing the clothing openings in strong wind to enhance heating efficiency.

ACKNOWLEDGMENTS

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