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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

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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

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

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^2K/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%

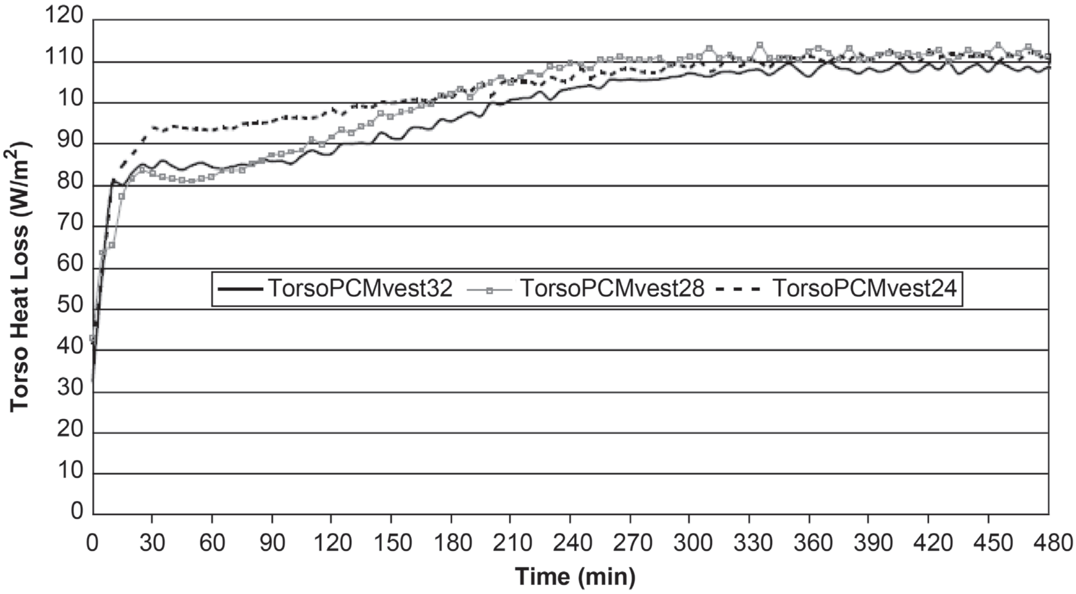

Figure 2. Heating effects of phase change material (PCM) vests (T_{melt} = 32, 28, and 24 °C) on the thermal manikin in the subzero environment [47].

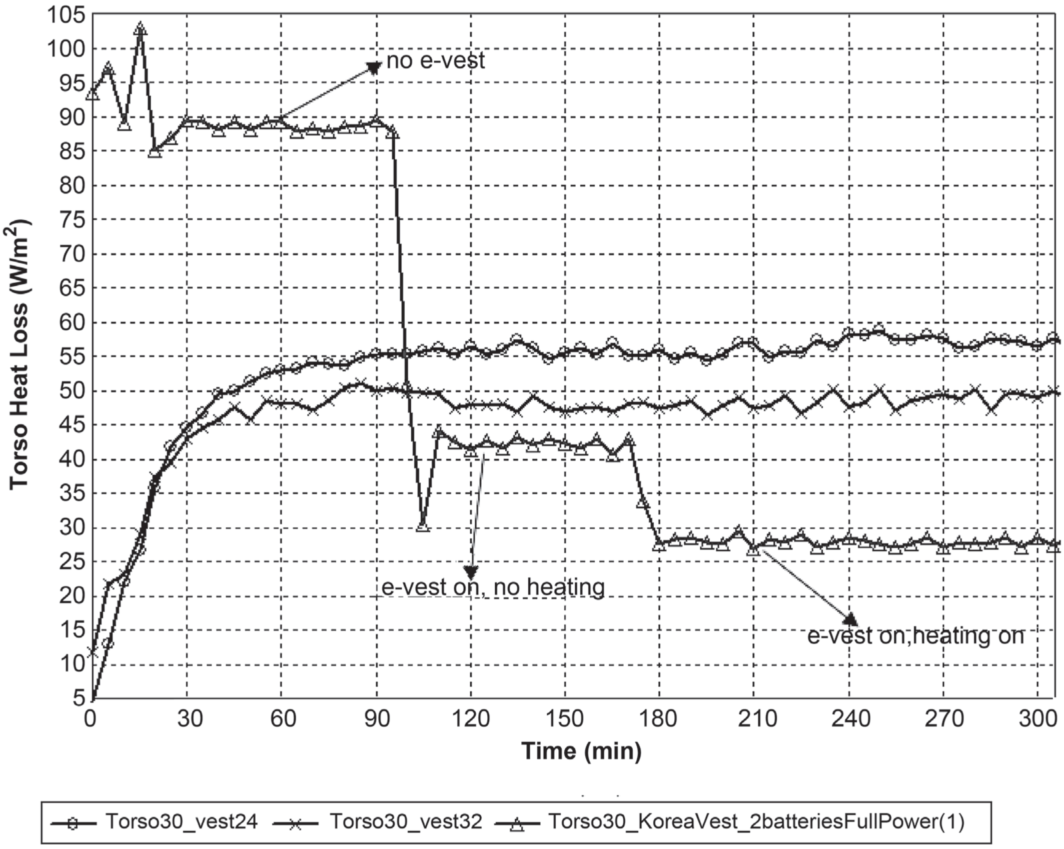

Figure 3. Manikin torso heat losses for phase change material (PCM) vests and electrical heating vest [34]. *Notes.* PCM vests worn over manikin stretch coverall, $T_{manikin}$ = 30 °C, T_a = –4 °C, V_a = 0.4 m/s.

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, 2200-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

$$2\mathrm{B}+\frac{3}{2}\mathrm{O}_2 \rightarrow \mathrm{B}_2\mathrm{O}_3+1.29 \quad \mathrm{kg}\cdot\mathrm{J/mol}. \tag{2}$$

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

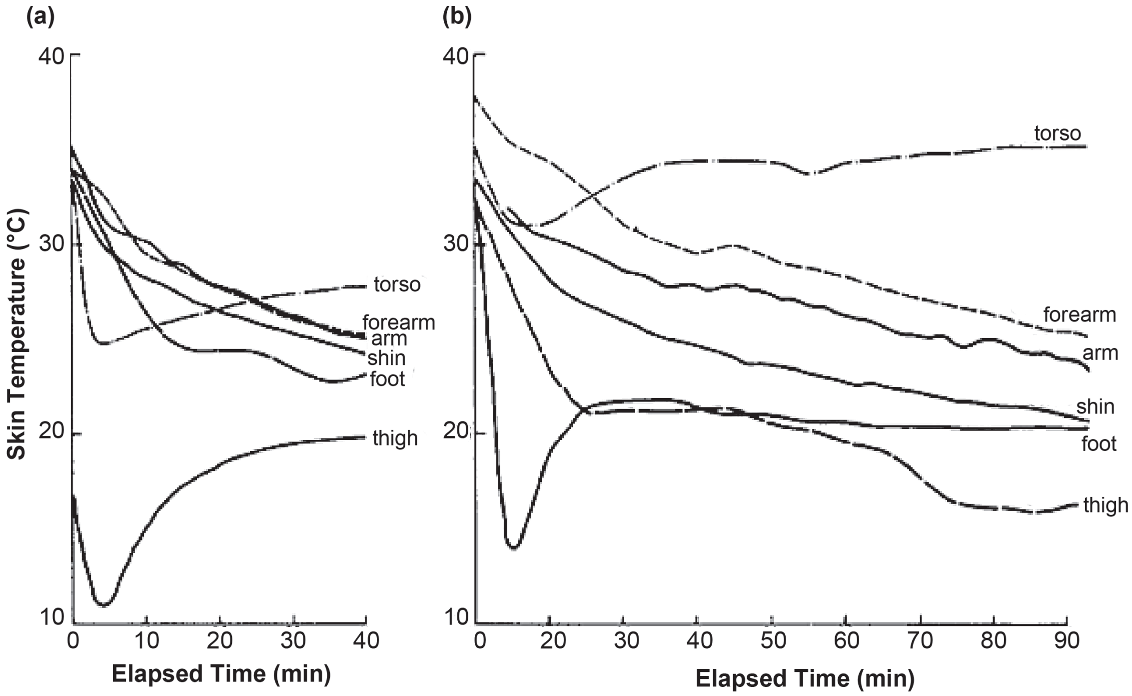

Figure 4. Skin temperatures for (a) unheated and (b) heated dives in 5 °C water [55].

(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:

$$Fe + \frac{3}{4}O_2 + \frac{3}{2}H_2O \rightarrow Fe(OH)_3 + 402 \quad \text{kJ/mol.} \tag{3}$$

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

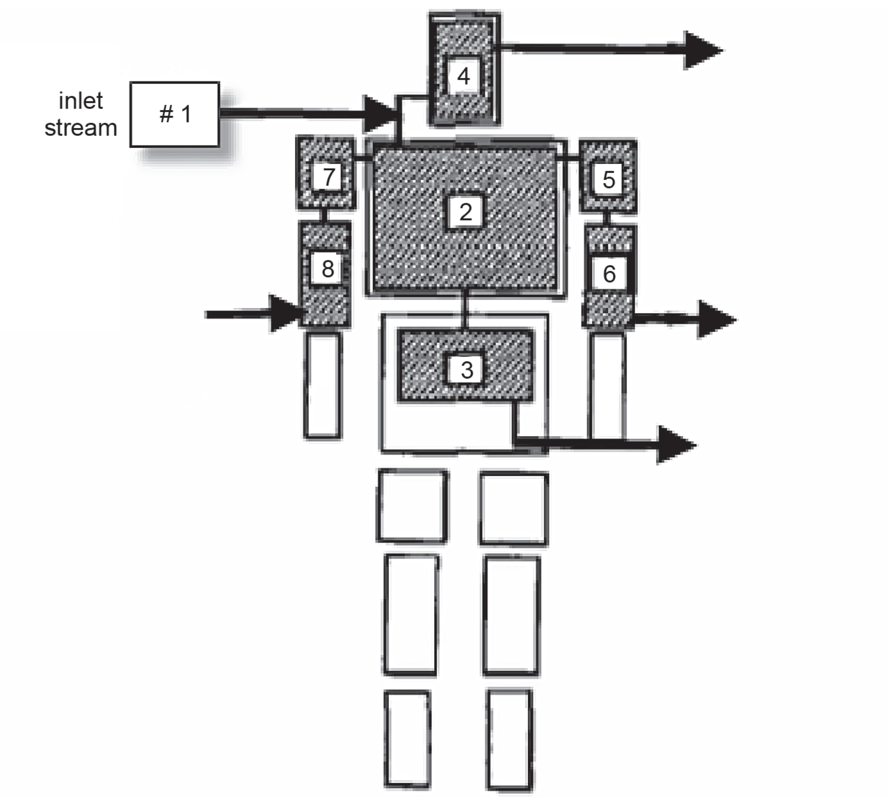

Figure 5. Schematic representation of heat exchanger elements and flow path used to form an air-warming vest [65].

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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