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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 × 250 × 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 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.

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

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, m^2; 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

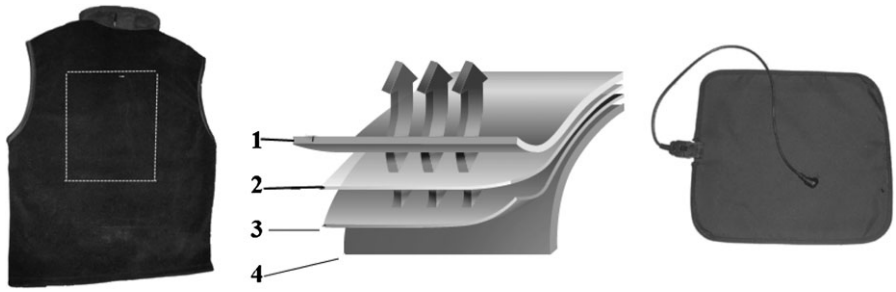


Fig. 1. The EHV and four-layer structure of the carbon polymer-heating element: (1) protection layer; (2) heat-insulating layer; (3) heat generating layer; and (4) base layer.

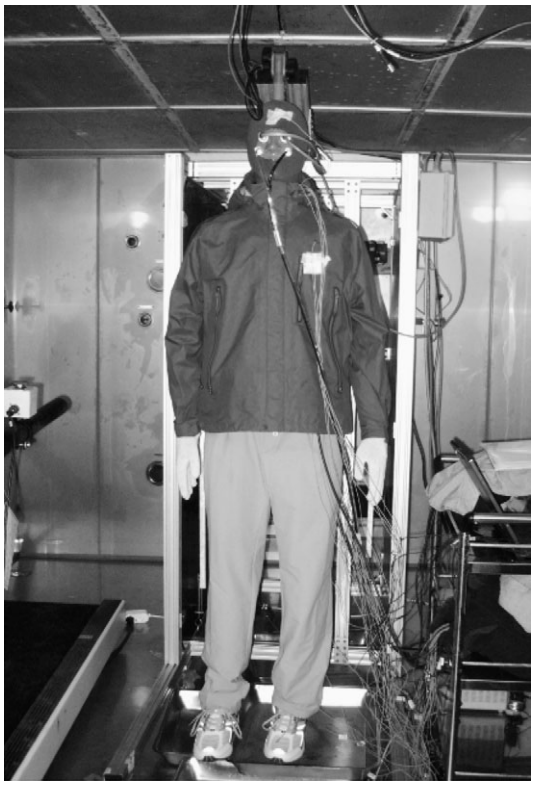


Fig. 2. The Newton thermal manikin in the climatic chamber.

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

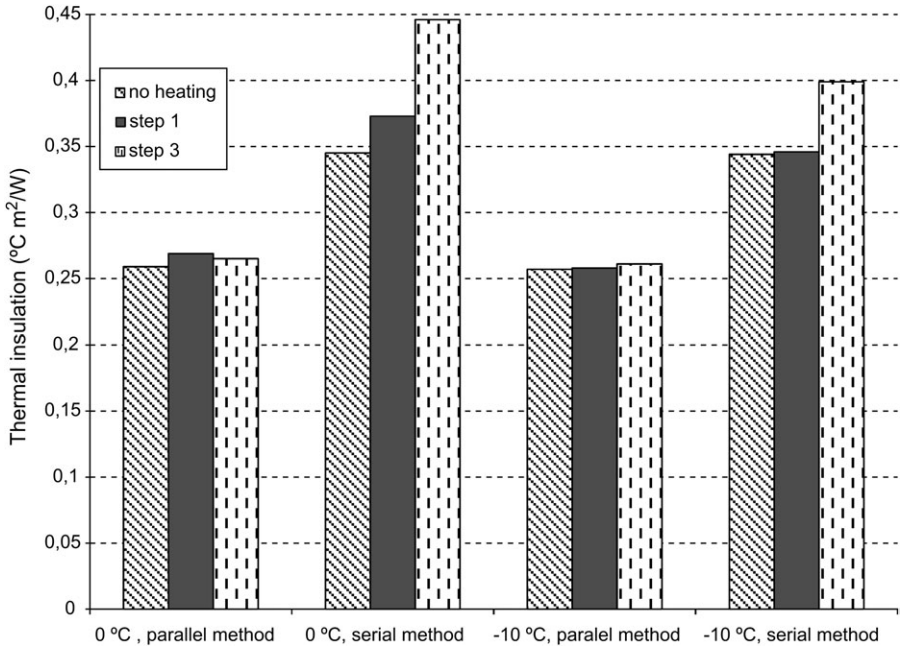


Fig. 3. Clothing total thermal insulations at different heating states, 0 and −10°C.

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

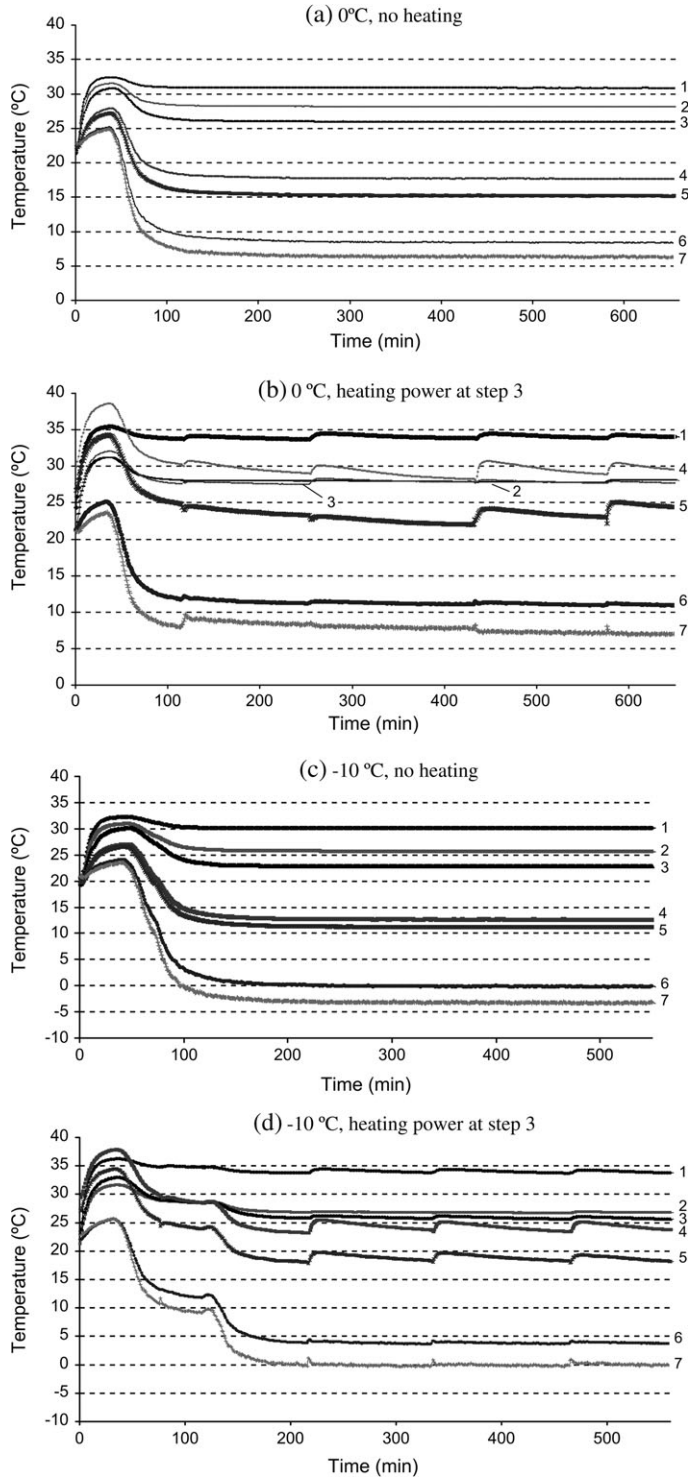
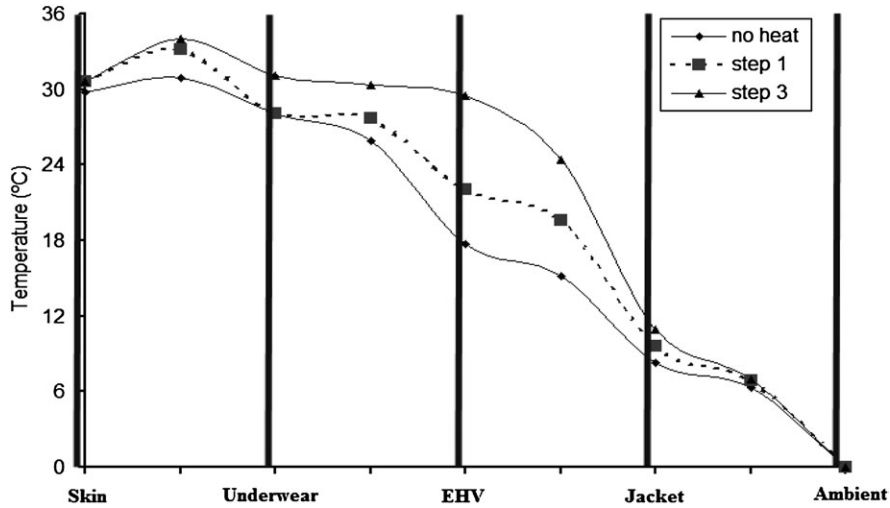
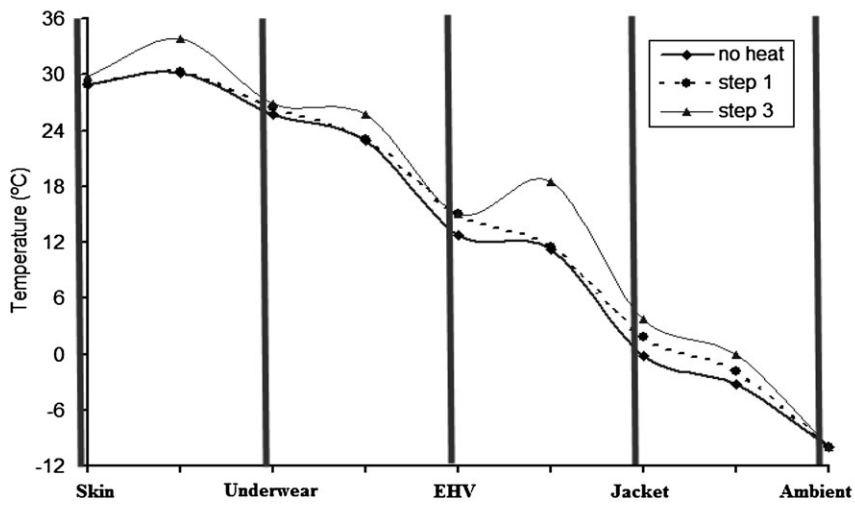


Fig. 4. The microclimatic temperature distribution of a three-layer clothing ensemble at 0 and −10°C. All values showed here are averaged temperatures measured from the chest and back sites of the clothing outer surface: (1) between skin and underwear; (2) on the underwear; (3) between the underwear 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 ºC;



(b) at -10 ºC.

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 improve 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.

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

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.

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